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Design Data for Brazed René 41 Honeycomb Sandwich

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FOREWORD

This report was prepared by the Boeing Aerospace Company, a Division of The Boeing Company, Seattle, Washington, for the Langley Research Center of the National Aeronautics and Space Administration. The mechanical properties of brazed Rene'41 honeycomb sandwich are presented in accordance with the requirements of Contract NAS1-14213, "Design Data for Brazed Rene'41 Honeycomb Sandwich." This program was originally under the cognizance of Herman L. Bohon and then the cognizance of John Shideler of the Langley Research Center.

The technical leader was J. L. Arnquist, reporting to the program manager, A. K. Hepler. The principal test investigator was E. L. Koetje. The analysis and documentation of the design data was conducted by J. J. Esposito and V. E. J. Lindsay and A. R. Swegle.

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SUMMARY

The objective of this program was to develop preliminary mechanical design properties for brazed Rene'41 honeycomb sandwich. Strength data, creep data and residual strength data after cyclic thermal exposure were obtained at temperatures ranging from 78K to 1144K (-320°F to 1600°F). The influences of face thickness, core depth, core gage, cell size, and thermal/stress exposure conditions on the mechanical design properties were investigated.

A braze alloy and process were developed that are adequate to fully develop the strength of the honeycomb core while simultaneously solution treating and ageing the Rene'41 face sheets.

Good mechanical design properties were obtained with adequate stability of these properties after cyclic exposure to high temperatures at low sustained stress levels. Face sheet tensile strengths are similar to those which result from other heat treating methods and the ductility of face sheet thicknesses of 0.533 mm (0.021 in.) and over is adequate for primary structure. Additional braze cycle development (variation of ageing time and temperature) is required to improve the ductility of thinner sheet. Core shear strength after stressed cyclic thermal exposure remains at a high percentage of the unexposed values, however, significant creep occurred during exposure. Residual edgewise compression strength was not sensitive to cyclic exposure at temperatures up to 1033K (1400°F) but degraded to approximately 50 percent of the unexposed values after 500 cycles at 1144K (1600°F) and low sustained stress.

New test procedures and test specimen configurations were developed to avoid excessive thermal stresses during cyclic thermal exposure.

INTRODUCTION

The successful development of advanced high-speed aircraft and space transportation systems is strongly dependent upon airframes which have high structural efficiency, which meet structural integrity, service life and maintainability requirements, and which are producible at reasonable cost. Airframes incorporating honeycomb core sandwich structure have been shown to meet these requirements, particularly where operational environments include high dynamic pressure, high sonic levels and relatively low axial loadings (XB-70, Shuttle Aft Body Flap, Radomes, Control Surfaces). Extensive design data have been developed for aluminum, titanium, stainless steel, and plastic honeycomb sandwich materials. Honeycomb structures incorporating these materials provide the capability to operate over a temperature range of 32K (-400^{0}F) to approximately 800K (1000^{0}F). An extended operating temperature range of 21K to 1144K (-420^{0}F to 1600^{0}F) is required for new designs. Rene'41 superalloy provides the basic material characteristics required to operate over this temperature range. The test program results presented in this report demonstrate that the basic material characteristics of Rene'41 can be translated into honeycomb sandwich panels. Use of these panels can significantly enhance the performance capability of high-speed, high surface temperature vehicles by reducing or eliminating parasitic insulation.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

TEST PROGRAM AND TEST PROCEDURES

The objective of the test program was to develop preliminary design data for brazed Rene'41 honeycomb sandwich structure. In addition to generating conventional short term data over a range of temperatures, residual strength data after cyclic thermal exposure typical of an operational environment and cyclic-life-to-failure data under sustained stress levels were obtained.

The influence of test temperature, cell size, core thickness, core ribbon direction and face thickness on the basic mechanical design properties of the sandwich were evaluated in the tests shown in Table 1. The influence of thermal exposure cycles and exposure stress levels on the mechanical design properties of the sandwich were evaluated in the tests shown in Table 2. Creep and thermal expansion data were obtained from the tests shown in Table 3.

Established ASTM and Boeing test specimens and test procedures were used to conduct the tests. A summary of the test specimen configurations and test procedures are shown in Figure 1. The barrel compression specimen was tested using procedures similar to the standard ASTM edgewise compression specimen procedures. The barrel compression specimen was developed by Boeing in the late 1960's to enable evaluation of the effects of local out-of-plane loads on the strength of honeycomb sandwich. The standard edgewise compression specimen was modified into the dog-bone configuration shown in Figure 2 for most of the tests outlined in Table 2 as discussed later.

The cyclic thermal exposure facilities were designed to automatically subject the specimens to a repeating temperature cycle while under a constant load. Banks of heat lamps were used to heat the specimens while the temperatures were automatically controlled and monitored using thermocouples attached to the specimens. The specimens were loaded during the thermal exposure using static dead weights to obtain the desired stress levels.

The mass of the loading blocks used to load the flatwise tension specimens made it impractical to thermally cycle the specimens with an applied load. The specimens were therefore thermally cycled without load and then exposed at a constant temperature with the applied stress as noted in Table 2.

The thermal exposure cycles used to conduct the testing are shown in Figure 3. The various thermal cycles evolved during the course of the program in an effort to simulate predicted reentry heating for the selected operational environment and to reduce specimen thermal gradients.

Raw test data are tabulated in Appendix A. U. S. customary units were used for all measurements and calculations.

MATERIAL

The Rene'41 face sheet material was purchased to AMS 5545. The sheet material was identified by heat lot numbers and the required specification inspection certification data were supplied by the vendors to Boeing. The Rene'41 foil material used to fabricate the honeycomb core was purchased to Rohr Material Specification RMS 109 from two foil suppliers, referred to herein as vendors A and B. The vendor A foil was delivered with a uniform oxide coating with a definite yellow cast. The preliminary Rene'41 brazing process was developed while using this foil. The vendor B foil contained approximately 60%

material with a bright silver satin finish and the rest of the material in various shades of yellow, none of which were as pronounced as the vendor A foil.

An evaluation of various braze alloys potentially suitable for use with Rene'41 had been conducted (Reference 1) and resulted in the development of a new braze alloy powder identified as AMI 930 FOB by Alloy Metals, Inc. The alloy designation was subsequently changed to AMI 937. No standard specification existed for this alloy, therefore, it was purchased to Boeing Aerospace Company engineering requirements. Two lots of braze alloy powder were used. The test data showed no variations between lots.

BRAZE PROCESS

The braze process selected for use in fabricating the honeycomb sandwich specimens was developed by the Boeing Aerospace Company. The process/braze alloy was required to: (1) have a brazing temperature of approximately 1350K (1975^{0}F) to be compatible with the solution treat temperature of the Rene'41, (2) flow sufficient to seal a short unwelded length of core node adjacent to each skin, (3) not erode or degrade the basic Rene'41 material.

The AMI 930 FOB braze alloy and the basic braze process satisfied these requirements and provided a means of fabricating lightweight, evacuated, and sealed Rene'41 honeycomb sandwich. Heat treatment/aging of the Rene'41 was accomplished during the braze cycle. Portions of a typical panel are shown in Figure 4.

The basic brazing process was developed with core fabricated from vendor A foil, and it included the following major features:

A. Application rate of braze alloy powder ▷

Core Cell Size		Top Surface		Bottom Surface	
mm	(in.)	gm/cm^2	(gm/in^2)	gm/cm^2	(gm/in^2)
9.5	(3/8)	0.093	(0.6)	0.093	(0.6)
6.4	(1/4)	0.124	(0.8)	0.093	(0.6)

▷ Braze alloy application rates are preliminary pending optimization studies. Top and bottom refer to position in braze furnace.

B. Braze cycle, in vacuum

1) Heat to 754K (900°F) and hold for 4 hrs to drive off alloy binder by-products;
2) Heat to 1200K (1700°F) to stabilize temperatures;
3) Heat to 1350K (1975°F) and hold for 5 min (brazing temperature);
4) Cool to 1200K (1700°F) and hold for 1 hr (aging temperature);
5) Furnace cool under vacuum to approximately 325K (125°F).

The basic brazing process had to be modified to obtain a proper brazed joint with vendor B foil. Small fillets, excessive braze alloy flow, and core erosion resulted when the basic process was used with vendor B foil. The braze process was modified to accommodate vendor B foil as follows:

(1) Clean the core blanket in an HNO_3/HF bath to strip surface oxides
(2) Heat the core blanket in air to 1144K (1600°F) and hold for 13 minutes to obtain a uniformly oxidized surface
(3) Lower the brazing temperature from 1350K to 1346K (1975°F to 1965°F).

TEST PANEL AND SPECIMEN FABRICATION

The brazed Rene'41 honeycomb sandwich panels were fabricated by Rohr Corp., in Chula Vista, California. The core blankets were fabricated to Rohr Material Specification RMS 110. The nodes of the core were partially seam welded.

Each panel was inspected using NDI techniques (visual and radiographic). In addition, samples from each panel were destructively tested for further assurance of panel integrity.

The test specimens were cut from the panels using a diamond cutting wheel to avoid crushing and tearing of the core material. The specimen identification numbering and typical panel cutting diagrams are contained in Appendix B. The "dog-bonded" edgewise compression specimens were electrical discharge machined.

Test specimens fabricated from the two different foils had significantly different properties, as discussed below.

TEST RESULTS

Face Sheet Tension

The face sheet tension tests were conducted with Baldwin Tate Emery Universal testing machines. The thermal exposure facility is shown in Figure 5. Half of the heat lamps have been lowered to display the specimens.

As-received material properties were determined to obtain a reference for future material purchase. Average values for the 0.533 mm (0.021 in.) nominal thickness were: F_{TU} = 988 MPa (143.2 ksi), F_{TY} = 579 MPa (84 ksi), elongation in 50.8 mm (2 in.) of 44.75 percent. For the 0.279 mm (0.011 in.) thickness, average values were:

> F_{TU} = 952 MPa (138 ksi), F_{TY} = 457 MPa (66.3 ksi), elongation in 50.8 mm (2 in.) of 44.7 percent.

Preliminary testing was conducted to determine the effect of specimen configuration on the test data. A comparison of the test data for various specimen configurations is shown in Figure 6. It would be desirable to use a fully machined (i.e., core fillets and braze alloy removed) specimen since the thickness of each specimen can be controlled; however, the testing showed that the results are highly dependent on the specimen surface condition and that a portion of the honeycomb core must be left on the specimen to obtain data directly applicable to honeycomb sandwich panels. A more detailed discussion of the preliminary testing is presented in Appendix C.

The specimens used to obtain the face sheet tension strength, modulus, and elongation data points and faired curves presented in Figures 7 and 8 were obtained by cutting apart brazed honeycomb panels and then machining the core down to the height of the braze alloy fillets. Since the individual specimens' effective thickness could not be measured, the stress levels were calculated by using the average sheet thickness determined prior to brazing. The nominal 0.508 mm (0.020 in.) sheet averaged 0.533 mm (0.021 in.) thick and the nominal 0.254 mm (0.010 in.) sheet averaged 0.279 mm (0.011 in.) thick.

The effect of the exposure condition of 100 cycles at 1090K and 172 MPa (1500^{0}F and 25 ksi) (Cycle E) was minimal, as seen in Figure 7.

The tensile yield and ultimate values obtained are similar to values obtained with other heat treating parameters (see Ref. 2). Therefore, the selected braze process is capable of developing the usable strength of the Rene'41. Although the elongation values are greatly reduced from base metal properties, the elongation of the 0.533 mm (0.021 in.) face sheet remains similar to that of other structural materials, i.e., 7075 aluminum, and is therefore suitable for use in primary structure. Further process development is required to improve the elongation of thinner sheet.

Because of the orientation of the panel with respect to gravity during the braze cycle, the possibility exists for greater node flow and smaller fillets on the top face of the panel, therefore, top and bottom faces were identified throughout the testing of the 0.533 mm (0.021 in.) skin. However, there was no difference in the test results, and the test values were combined to compute the average values shown in Figures 7 and 8.

Tensile Creep

Tensile creep testing was conducted using Riehle 88,920 Newton (20,000 pound) tensile creep test machines (Figure 9).

The creep test specimens were prepared in the same manner as the tensile test specimens. Approximately one-half of the test specimens were exposed to 1090K at 172 MPa (1500^{0}F at 25 ksi) for 100 thermal cycles (Cycle E) prior to creep testing. The remaining specimens were as-brazed.

The initial temperature and applied stress levels chosen for the creep testing were estimated from data in Reference 2 for Rene'41 heat treated to similar conditions. Both the as-brazed and exposed specimens exhibited creep rates of two to ten times the predicted rate.

Additional as-brazed specimens were then added to the test program with temperature/applied stress parameters re-estimated to produce failure at approximately 50 hours. The Larson-Miller data analysis method was then used to select parameters for continued testing. Data scatter was minimal and excellent correlation with the Larson-Miller predictions was achieved. The Larson-Miller constant was determined to be 25.9 for as-brazed specimens.

Test results are summarized in the Larson-Miller plot in Figure 10. Creep curves for individual specimens are shown in Figures 11 through 16.

As seen in Figure 10, the 100 cycle exposure involving a total of approximately 10 hours at 1090K and 172 MPa (1500°F and 25 ksi) has a significant effect on the remaining time to rupture. As an example, at 345 MPa and 1033K (50 ksi and 1400°F) the exposed specimens would be predicted to rupture in 50 hours while the as-brazed specimens would be predicted to rupture in 100 hours. Differences in the behavior of exposed versus as-brazed specimens can also be seen in Figures 11, 12 and 15.

Peel Strength

Figure 17 shows a peel strength test in progress. An average room temperature peel strength of 0.886 J/mm (16.6 in-lb/in.) was obtained for the 4-15 core panels and 0.769 J/mm (14.4 in-lb/in.) for the 6-15 core panels in the as-brazed condition. All the individual peel strengths, except one, exceeded the 0.534 J/mm (10 in-lb/in.) established as an acceptance guideline for the honeycomb sandwich panels. This guideline value is the peel strength estimated to produce core yielding for the 6-15 core.

After exposure, the average residual peel strength was 0.634 J/mm (11.9 in-lb/in.) for the 6-15 core, which still exceeds the guideline value. Thermal exposure for these specimens consisted of 500 cycles (Cycle C) to a maximum temperature of 1033K (1400°F). Thus, it is concluded that the peel strength of the brazed Rene' honeycomb is adequate for primary structure applications.

Flatwise Core Tension

Figure 18 shows the flatwise tension test setup. Figure 19 summarizes the tests and analysis of flatwise tension capabilities. The predicted curves for the as-brazed condition were calculated using the ratio of the core density to the Rene'41 density (p_c/p) times the estimated F_{tu} of the 0.038 mm (0.0015 in.) Rene'41 foil. Estimated F_{tu} was 983 MPa (143 ksi).

All test data fell substantially below the predicted curves. However, all the failures were in the core. The braze alloy fillets did not fail and the braze alloy did not degrade the Rene'41 foil adjacent to the fillets. One explanation may be the difficulty of obtaining uniform loading on the specimen or the estimated F_{tu} may be too high for the heat treat condition of the foil. In order to directly determine the foil strength, it would be necessary to remove a sample from a brazed panel. Test procedures and equipment for testing such small specimens were not available.

The thermal exposure specimens were exposed without load to Cycle B. Following cyclic exposure, the specimens were brazed at 1260 K (1810°F), to loading blocks and then exposed at a constant temperature of 1033K (1400°F) with an applied stress of 0.59 MPa (85.7 psi) (based on face sheet area). The 100 cycle specimens were exposed for 7.5 hours and the 500 cycle specimens were exposed for 37.5 hours. In order to differentiate between the effects of the cyclic temperature exposure only and the combined temperature and stress exposure, one set of specimens was exposed to the same conditions as the above 100 cycle specimens except without an applied stress. The average room temperature residual strength of these three specimens was essentially identical to the stressed specimens.

The as-brazed room temperature specimens had an average ultimate strength of 6.69 MPa (971 psi), the specimens cyclicly exposed without any stress had an average ultimate strength of 6.49 MPa (941 psi), and specimens exposed with an 0.59 MPa (85.7 psi) applied stress had an average residual strength of 6.03 MPa (874 psi) at room temperature.

The 1144K (1600^oF) strength of the 500 cycle exposure specimens was 2.52 MPa (365.7 psi) as compared to the 100 cycle exposure specimen strength of 2.48 MPa (360.3 psi) and an unexposed strength of 2.96 MPa (429.3 psi). Therefore, the cyclic exposure did not substantially effect the strength. Overall evaluation of the results shows only moderate loss in capability up to 922K (1200^oF) followed by a rapid decrease to less than 50% of the room temperature strength at 1144K (1600^oF).

Flatwise Core Compression

The test setup for core compression was similar to that used for flatwise tension. The predicted room temperature core compression properties shown in Figure 20 were calculated using the empirical equation $F_{cc} = k\ (\rho_c/\rho)^n$. The values of k and n were estimated from existing data on noncorrugated square cell annealed Rene'41 core. The ratio of the core density to Rene'41 density (ρ_c/ρ) for the 6-15 core is 0.00893 and is 0.0134 for the 4-15 core. The curves for elevated temperature were estimated using the effect of temperature on E_c of the base metal.

The average test data falls near the predicted curves as shown in Figure 20. Thus, it is concluded that flatwise core compression strength varies with temperature as a function of compression modulus of the core base metal. Therefore, the effects of cyclic thermal exposure were not determined experimentally since it appears that the effects of exposure can be predicted from the base metal behavior.

Core Shear

The core shear test setup is shown in Figure 21.

Figure 22 summarizes the predicted strengths and test results for the as-brazed specimens. The predicted core shear strengths shown in Figure 22 were derived from test data for square cell Rene'41 honeycomb core with flat cell walls. The honeycomb core used in this program had corrugated cell walls and thus, higher densities for specific cell sizes and foil thicknesses. This effect is reflected in the predictions. Test results are in close agreement with the predicted values for the low density core but as much as ten percent low for the higher density. The reason for the low values could not be determined but could reflect the limited data base or variation in core foil thickness from nominal.

All specimens failed in the core foil thereby indicating that the braze process is adequate to fully develop the foil properties.

A reduction in core shear strength is normally associated with increasing core thickness. This effect is not apparent in the test data, however, this may be the result of the limited data base and data scatter.

Some data scatter is caused by the varying number of continuous ribbons between specimens. The 6-XX core specimens have either 9 or 10 ribbons and 4-XX specimens have either 14 or 15 ribbons. The data shown has not been modified to account for this effect.

Room temperature core shear strength versus core density is shown in Figure 23. By comparing average results and grouping both 19.05 mm and 30.48 mm deep specimens, the transverse direction core strength was determined to be 88 percent of the longitudinal direction for 6-15 core and 73 percent for 4-15 core at room temperature.

The effect of thermal exposure on residual strength is shown in Figures 24 through 28. Figures 26 and 27 indicate some effect of exposure stress level. The 6-15 specimens exposed at 14.8% of their as-brazed room temperature strength typically exhibit lower residual strengths than those exposed at 7.4 percent. Although a considerable amount of creep deformation occurred during thermal exposure, the residual strength data does not show a definitive pattern of change of residual strength with increasing number of thermal cycles.

Shear Creep

Three vendor A specimens were loaded to 0.41, 0.20 and 0.14 MPa (60, 30 and 20 psi), respectively in the fixture shown in Figure 21, and their mid-span deflection was measured periodically during exposure to thermal Cycle E (1090 K, 1500^{o}F).

The specimen loaded to 0.41 MPa (60 psi) failed near the end of the first thermal cycle, due to creep shear buckling of the core. The specimen loaded to 0.20 MPa (30 psi) failed at 42 cycles due to local crushing of the core under the load head. The specimen loaded to 0.14 MPa (20 psi) failed at 283 cycles due to creep shear buckling of the core. The deflection plotted in Figure 29 is the deflection at mid-span with the specimen under load and at room temperature. The allowable creep deflection is dependent on the specific application, however, a creep deflection of 5.0% of the specimen semispan was adopted as a guideline damage threshold for this program. This guideline was exceeded at one cycle for the 0.41 MPa (60 psi) specimen and at 200 cycles for the 0.14 MPa (20 psi) specimen.

To obtain exposure stress levels for the vendor B specimens, the vendor A data was extrapolated using the Larson-Miller data analysis method. Stress levels were chosen so that the 5 percent creep deflection limit would not be exceeded at the desired exposures of 200 and 500 cycles.

Actual test results for the Vendor B core showed significantly lower creep rates than the Vendor A core (see Fig. 29). The reason for the differing behavior is not understood. Other data, as shown in the next section, indicate that specimens fabricated from Vendor A foil exhibit better properties than Vendor B.

Figure 30 shows typical specimen after exposure.

Edgewise Compression and Barrel Compression

An edgewise compression test set up is shown in Figure 31.

Vendor A Foil

Initial testing included standard specimens with parallel faces as well as barrel specimens with curved faces. The barrel specimens were used to evaluate the effect of curvature on the strength of honeycomb panels.

Predictions and test results are shown in Figure 32 for the 0.279 mm (0.010 in.) face sheet and in Figure 33 for the 0.533 mm (0.020 in.) face sheet.

The predicted curves shown in Figures 32 and 33 were calculated for parallel faced specimens, using the predicted Rene'41 base metal properties to define compression yield capabilities. Intracell buckling predictions were defined by using the equation:

$$\frac{F_c}{E_t} = \frac{\pi^2}{3(1-\mu^2)} \left(\frac{t}{s} \right)^2$$

where: F_c is the buckling stress

E_t is the compression tangent modulus developed from the compression stress strain diagram for the Rene'41 base metal

t = sheet thickness

s = cell edge length

Results of both cyclicly exposed and unexposed tests at various temperatures indicated strength somewhat above the predicted compression yield value and significantly above the intracell buckling predictions for both the 0.279 mm 0.011 in.) and 0.533 mm (0.021 in.) gage face sheet specimens at temperatures up to 922K (1200°F). The tests at 1144K (1600°F) however, showed a significant drop below the predicted compression yield value.

The parallel faced and curved face specimens behaved in a similar manner, thereby indicating that the curvature used in the test specimens does not degrade the honeycomb panel strength.

The results at 1144K (1600°F) were affected by a deterioration of the core in the end portions of the specimens. This deterioration was caused by chemical attack by the cement potting compound used to stabilize the end area of the specimens. Deterioration of the core material at temperatures above 1033K (1400°F) was seen on all specimens which used the potting compound. Figure 34 shows an example of a specimen with a deteriorated core. Clamps were used at the ends of the specimen in an attempt to stabilize the deteriorated core material, however, the low test results at 1144K (1600°F) are probably still attributable to this effect. The test specimen was modified for all later tests in a manner which eliminates the need for the end potting compound and end clamps. The modified specimen is shown in Figure 2. The validity of this modified specimen was demonstrated by the static test point shown in Figure 33 at 1090K (1500°F). This specimen failed by face wrinkling in the central portion of the specimen at a stress level above the predicted compression yield of the face sheet material and was therefore consistent with results at lower temperatures.

The 4-XX core specimens identified by the small open circle symbols in Figure 33 showed failure stresses significantly higher than the 6-XX core specimens and about 20 percent above the predicted compression yield of the face material. These high values can be attributed to increased ability of the smaller cell to stabilize the 0.533 mm (0.020 in.) skin above the yield point combined with the heavier coating of braze alloy used on the 4-XX core specimens.

Results of residual strength static tests after cyclic thermal exposure of the specimens is shown by the solid symbols in Figure 32 and Figure 33. The specimens were exposed to 100 cycles of thermal cycle C with a maximum temperature of 1033K (1400°F). An externally applied compression stress of 68.9 MPa (10 ksi) was maintained throughout the cyclic exposure. Residual strengths were consistently equal to or above the original static strength at all temperatures.

Transient thermal gradients in these specimens were found to be 700K (800°F) between the center and ends of the specimen during the thermal cycling due to the heat sink effect of the potting compound and the loading blocks, i.e., the ends of the specimens remain cool compared to the center. Analysis of these thermal gradients indicated compressive thermal stress levels of 124 MPa (18 ksi) were induced in the specimen during some portions of the thermal cycle. Experimental verification of the stress levels was not feasible because strain measuring devices small enough to measure the high gradient and operate at the high temperature were not available. Although the residual strength data obtained from these specimens is conservative, these high thermal stresses were considered unacceptable for definitive test data. Therefore, the modified test specimen was used for further testing. This specimen along with modifications to the loading blocks and heater banks reduced the thermal gradients to levels which resulted in thermal stresses calculated at less than 34 MPa (5 ksi).

Several unsuccessful attempts to conduct thermal cyclic testing on the original specimen at higher temperatures and higher external stress levels are outlined in Appendix D. Thermal analysis results are outlined in Appendix E.

Threshold definition testing was conducted using the modified specimen to predict the effect of applied external compressive stress on cyclic life. Results of these limited tests are shown in Figure 35. Three specimens were cycled to failure using Cycle E at 379, 310 and 241 MPa (55, 45, and 35 ksi) externally applied compressive stress. Failures were face wrinkling types in the central portion of the specimen. These test results were extrapolated using the modified Larsen-Miller type creep relationships shown in Figure 36, (Vendor A line). The exposure stress levels for additional testing were selected by this means to preclude specimen failure during thermal cycling.

Vendor B Foil

Thermal exposure of specimens fabricated from Vendor B core foil commenced with the 1090K (1500^{0}F) specimens stressed to 241.3 MPa (35 ksi) and failure occurred after six cycles. The predicted life based on the Vendor A data was approximately 500 cycles. A strain gaged specimen was installed in the thermal exposure facility and verified that the early failure was not due to unbalanced loading. Exposure of additional specimens to the same conditions verified that the initial early failure was not an isolated occurrence. Photographs of typical failures are shown in Figures 37 through 39. Specimens were then exposed to other stress and temperature combinations until sufficient data was available to reliably choose stress levels compatible with the 500 cycle desired life (Vendor B line of Fig. 36).

Qualitative examination of the core foil from the failed specimens showed that the Vendor B foil had become embrittled during the thermal exposure to a significantly greater extent than the Vendor A foil. Contamination from the EDM process was suspected as the cause. However, photomicrographs of foil with similar thermal exposure that had not been subjected to the EDM process were compared to photomicrographs of foil from the failed specimens with inconclusive results. Similar comparisons between Vendor A and Vendor B foils showed that the surface reactions on each side of the 6-15 Vendor B foil extended through approximately twenty percent of the material thickness while only minor surface reactions were noticed on the Vendor A foil. This difference in surface reactions can be seen in Figure 40. Further analysis to explain the differing behavior of the foils was beyond the scope of this program.

Results of the residual strength testing with Vendor B foil are shown in Figures 41 through 45. The as-brazed data in Figure 41 for Vendor B specimens is essentially identical to the results for Vendor A specimens. Residual strength data for the exposed specimens fabricated with Vendor B foil were widely scattered and the results are inconclusive. The effect of exposure shown in Figure 41 is only intended to indicate possible trends. The points plotted are averages of individual data points that are widely scattered. The data used for the curves in Figure 41 are shown in Figure 44 and indicate the extent of the data scatter. The effect of stress level during thermal cycling is indicated in Figures 42, 43, and 44 for the three exposure conditions. Again, the trend lines are based on extremely limited data.

The effect of core foil thickness on residual compressive strength is shown in Figure 45. The 6-15 core data for the 103.4 MPa (15 ksi) exposure condition has been replotted from Figure 43 for a direct comparison with 6-25 core specimens exposed to the same conditions. As seen, the residual strength of the 6-25 core at both room and elevated temperature remains essentially unchanged from the as-brazed (zero cycle) values. Increasing residual strengths with increasing core foil thickness are to be expected since the depth of the surface reactions become a smaller percentage of the foil thickness.

Failure Modes

The edgewise compression failure mode was face wrinkling for all 6-15 core as-brazed specimens. Failures were exclusively face wrinkling for residual strength room temperature specimens for the 1033K (1400^oF) and 1090K (1500^oF) exposures. For these exposures, elevated temperature residual strength specimens failed by both face wrinkling and shear crimping in approximately equal proportions. Shear crimp failures were predominant in those specimens tested at both room temperature and 1144K (1600^oF) after exposure to the 1144K (1600^oF) thermal cycle. All 6-25 core specimens failed by face wrinkling.

Progressive visible damage occurred on many of the specimens during the thermal exposure. The damage consisted of dimpling at the specimen edges which progressed across the specimen with successive thermal cycles. Typical damage can be seen in Figure 39 (the face separation was caused by the "following" load when one face of the specimen slipped from the load blocks). The failures during exposure cycling were not directly dependent on the extent of the dimpling damage. Many of the failures occurred on specimens that had no prior discernible damage. "Threshold" combinations of stress/temperature/cycles at which dimpling was observed are (1) 1033K (1400^oF); no dimpling observed, (2) 1090K (1500^{o}F); dimpling occurred at 241.3 MPa (35 ksi) and 120.7 MPa (17.5 ksi) after 200 cycles for 6-15 core. No dimpling occurred at 103.4 MPa (15 ksi) after 360 cycles for 6-25 core; (3) 1144K (1600^{o}F); dimpling occurred at 34.5 MPa (5 ksi) and 51.7 MPa (7.5 ksi) after 200 cycles and at 68.9 MPa (10 ksi) after 100 cycles. The number of cycles shown is the upper limit for initiation of dimpling. The specimens were not continuously observed during thermal exposure.

Thermal Expansion

Thermal expansion characteristics were obtained from two as-brazed specimens of 0.533 mm (0.021 in.) face sheet. The averaged results are shown in Figure 46. The results are essentially identical to data obtained from Reference 2 for other forms of Rene'41.

CONCLUDING REMARKS

Design data were obtained for different core densities and two face sheet thicknesses of brazed Rene'41 honeycomb sandwich panels.

The braze alloy and braze process developed are adequate to fully develop the strength of the honeycomb core. The braze process forms the brazed joint between the face sheet and core while solution treating and ageing the Rene'41. Resulting ultimate strength of the face sheet material is approximately 85% of Rene'41 subjected to the heat treat cycle without braze alloy. Yield strength increased slightly while elongation decreased. The elongation of 0.533 mm (0.021 in.) face sheets remains satisfactory for structural applications. Additional process development is required to improve the elongation of thinner material.

The tensile creep rate for the as-brazed face sheet material was significantly higher than literature data for similar forms of Rene'41. Cyclic thermal/stress exposure increased the creep rate over the as-brazed condition with a corresponding shorter time to rupture.

Honeycomb core fabricated from Rene'41 foil from two different vendors showed significantly different behavior during cyclic thermal exposure. Core fabricated from Vendor A foil exhibited a core shear creep rate approximately 150% to 200% higher than Vendor B foil. Both foils exhibited relatively high core shear creep rates. When thermal cycled to a peak temperature of 1090K (1500°F) with a constant shear stress of 0.138 MPa (20 psi), Vendor A core reached 2% shear creep strain after 50 cycles and Vendor B core reached 2% strain at 100 cycles. Both cores retained a high percentage of their as-brazed core shear strengths after cyclic thermal exposure.

Differing core behavior was also encountered during edgewise compression testing. Specimens fabricated with Vendor B core foil had a time to failure during thermal exposure cycling of only 2% to 4% of Vendor A specimens. As an example, if cycled at a sustained face compression stress of 138 MPa (20 ksi) with a peak temperature of 1144K (1600°F). Vendor A specimens would be predicted to fail after 500 cycles while Vendor B specimens would be predicted to fail at 10 cycles. Inspection of the failed specimens showed that Vendor B core foil had become severely embrittled as compared to the Vendor A foil. Photomicrographs showed that surface reactions on each side of the Vendor B foil extended to a depth of approximately 20% of the foil thickness while surface reactions on Vendor A foil were almost non-existent. The edgewise compression failure mode was primarily symmetrical face wrinkling for as-braced specimens and residual strength specimens tested at room temperature.

Shear crimp failures became predominant with increased testing temperature. For the conditions tested, residual strengths after cyclic thermal exposure generally decreased with increasing exposure temperature, increasing stress level, and increasing number of exposure cycles but remain at acceptable levels. Significant scatter in the Vendor "B" edgewise compression residual strength data prohibited determination of consistent trends.

Additional metallurgical studies are required to identify the reason for the differing behavior of core foils from different vendors.

Additional mechanical properties testing is required to fully define the sandwich core shear creep characteristics and the effect of stressed cyclic thermal exposure.

REFERENCES

1. Arnquist, J. L. and Hepler, A. K., Development of Brazed Rene'41 Honeycomb Structure. AIAA Paper 78-481, April, 1978.

2. Aerospace Structural Metals Handbook, Volume 5, Revised December 1979.

Table 1: Test Matrix (Specimens with No Thermal Exposure)

TEST TYPE NO.	TEST TYPE	SKIN GAGE mm (in.)	CORE TYPE ▷1	CORE FOIL VENDOR	CORE DEPTH mm (in.)	NUMBER OF SPECIMENS AT EACH TEST TEMPERATURE								
						76K (-320°F)	218K (-65°F)	297K (75°F)	755K (900°F)	811K (1100°F)	922K (1200°F)	1033K (1400°F)	1090K (1500°F)	1144K (1600°F)
1	FACE TENSION; BASEMETAL, AS RECEIVED	0.279 (0.011)						3			3			
		0.533 (0.021)						3			3			
2	FACE TENSION; BRAZE THERMAL CYCLE	0.279 (0.011)						3			3			
		0.533 (0.021)						3			3			
3	FACE TENSION; AS BRAZED, FILLETS & ALLOY OFF	0.279 (0.011)						2						
4	FACE TENSION; AS BRAZED, FILLETS OFF, ALLOY ON	0.279 (0.011)					3	16	3		3			
		0.533 (0.021)						3			2			
5	FACE TENSION; AS BRAZED FILLETS ON	0.279 (0.011)						7						3
		0.533 (0.021)				2		7		2	1	2		2
6	FACE COMP; BASEMETAL AS RECEIVED	0.533 (0.021)						3			3			
7	FACE COMP; BRAZE THERMAL CYCLE	0.533 (0.021)						3			3			
8	CORE SHEAR; AS BRAZED	0.533 (0.021)	6-15 (L)	A	19.05 (0.75)		3	10	3		3		1	7
			6-15 (W)	A	19.05 (0.75)			5			3			
		↓	6-15 (L)	A&B	30.48 (1.2)			5			3	1		
			6-15 (W)	A	30.48 (1.2)			3			3			
			4-15 (L)	A	19.05 (0.75)		3	5			3			3
			4-15 (W)	A	19.05 (0.75)			8			3			
			4-20 (L)	B	30.48 (1.2)			2					2	
		0.533 (0.021)	6-25 (L)	B	30.48 (1.2)			2					1	

Table 1: Concluded

TEST TYPE NO.	TEST TYPE	SKIN GAGE mm (in.)	CORE TYPE [1]	CORE FOIL VENDOR	CORE DEPTH mm (in.)	NUMBER OF SPECIMENS AT EACH TEST TEMPERATURE								
						76K (-320°F)	218K (-65°F)	297K (75°F)	755K (900°F)	811K (1100°F)	922K (1200°K)	1033K (1400°F)	1090K (1500°F)	1144K (1600°F)
9	EDGEWISE COMPRESSION	0.279 (0.011)	6-15 (L)	A	19.05 (0.75)		3	11	3		3			3
		0.533 (0.021)	6-15 (W)	A	19.05 (0.75)				5		3			3
		0.533 (0.021)	6-15 (L)	B	30.48 (1.2)				4			3	3	2
		0.533 (0.021)	6-25 (L)	B	30.48 (1.2)				1					
10	BARREL COMPRESSION	0.533 (0.021)	4-15 (L)	A	19.05 (0.75)			5			3			
			6-15 (L)	A	19.05 (0.75)		3	5	3		3			3
11	FLATWISE TENSION	0.533 (0.021)	4-15	A	19.05 (0.75)			5			3			3
			6-15	A	19.05 (0.75)		3	10	3		3			3
12	CORE COMPRESSION	0.533 (0.021)	4-15	A	19.05 (0.75)			5			3			3
			6-15	A	19.05 (0.75)		3	5	3		3			3
13	PEEL STRENGTH	0.533 (0.021)	4-15	A	19.05 (0.75)			5						
			6-15	A	19.05 (0.75)			5						

[1] FIRST NUMBER IS CELL SIZE IN 1/16THS OF AN INCH (1.5875 MM) SECOND NUMBER IS CORE FOIL GAGE IN TEN THOUSANTHS OF AN INCH (0.00254 mm). ALL ARE SQUARE CELL, CORRUGATED, NON-PERFORATED.

(L) INDICATES CORE RIBBON IN LONGITUDINAL SPECIMEN DIRECTION.

(W) INDICATES CORE RIBBON IN TRANSVERSE SPECIMEN DIRECTION.

Table 2: Thermal & Load Exposure Testing Matrix

TEST TYPE NO.	TEST TYPE	SKIN THICK. mm (in.) NOMINAL	CORE DEPTH mm (in.) NOMINAL	CORE TYPE ▷1	CORE FOIL VENDOR	EXPOSURE CYCLE & NUMBER OF CYCLES	EXPOSURE STRESS LEVEL GPa (ksi)	NUMBER OF RESIDUAL STRENGTH SPECIMENS AT EACH TEMPERATURE								
								76K (-320°F)	297K (75°F)	755K (900°F)	811K (1000°F)	922K (1200°F)	1033K (1400°F)	1090K (1500°F)	1144K (1600°F)	▷ THRESHOLD
14	FACE TENSION	0.279 (0.011) ▷				A 100	0.184(26.7)		3			3				
						A 100	0.211(32.1)		3			3			3	
						A 300	0.221(32.1)		3			3				
						A 500	0.221(32.1)		3			3				
						A 100	0.259(37.5)		3			3				
15	FACE TENSION	0.533 ▷ (0.021)				E 100	0.172(25.0)	2	2		2				2	
16	PEEL	0.533 (0.021)	19.05 (0.75)	6-15	A	C 500	0		4							
						F 500	0		1							
17	FLATWISE TENSION	0.533 (0.021)	19.05 (0.75)	6-15	A	B 100	▷		3						3	
						B 100	▷		3							
						B 100	▷								3	
18A	CORE SHEAR	0.533 (0.021)	19.05 (0.75)	6-15	A	C 100	88.9(12.4)		3			3			3	
				6-15	A	C 500	88.9(12.4)								3	
18B	CORE SHEAR	0.533 (0.021)	30.48 (1.2)	6-15	A	E	413.6 (60)									1
				↓	A	E	206.8 (30)									1
					A	E	137.8 (20)									1
					B	D 100	296.4 (43)		2				2			
					↓	D 200	296.4 (43)		2				2			
						D 500	296.4 (43)		2				2			
						D 100	148.2(21.5)		2				2			
						D 200	148.2(21.5)		2				2			
						D 500	148.2(21.5)		2				2			
						E 100	137.8 (20)		2					2		
						E 200	137.8 (20)		2					2		
						E 500	137.8 (20)		2					2		
						E 100	68.9 (10)		2					2		
						E 200	68.9 (10)		2					2		
				6-15		E 500	68.9 (10)		2					2		
				4-20		E 100	275.7 (40)		2					2		
				4-20		E 200	275.7 (40)		2					2		
				4-20		E 500	275.7 (40)		2					2		
				6-25		E 100	227.5 (33)		2					2		
				6-25		E 200	227.5 (33)		2					2		
				6-25	B	E 500	227.5 (33)		2					2		

Table 2: Concluded

TEST TYPE NO.	TEST TYPE	SKIN THICK. mm (in.) NOMINAL	CORE DEPTH mm (in.) NOMINAL	CORE TYPE [1]	CORE FOIL VENDOR	EXPOSURE CYCLE & NO. OF CYCLES [2]	EXPOSURE STRESS LEVEL GPa (ksi)	NO. OF RESIDUAL STRENGTH SPECIMENS AT EACH TEMPERATURE 76K (-320°F)	297K (75°F)	755K (900°F)	811K (1000°F)	922K (1200°F)	1033K (1400°F)	1090K (1500°F)	1144K (1600°F)	[3] THRESHOLD
19A	EDGEWISE COMPRESSION	0.279(.011)	19.05 (.75)	6-15	A	C 100	0.069 (10)		3	3		3			3	
				6-15	A	E	0.379 (55)									1
		0.533 (0.021)	30.48 (1.2)	6-15	A	E	0.310 (45)									1
				6-15	A	E	0.241 (35)									1
19B				6-15	B	D 100	0.621 (90)		2				2			
						D 200	0.621 (90)		2				2			
						D 500	0.621 (90)		2				2			
						D 100	0.310 (45)		2				2			
						D 200	0.310 (45)		2				2			
						D 500	0.310 (45)		2				2			
						E 100	0.241 (35)		2					2		
						E 200	0.241 (35)		2					2		
						E 500	0.241 (35)		2					2		
						E 100	0.121(17.5)		2					2		
						E 200	0.121(17.5)		2					2		
						E 500	0.121(17.5)		2					2		
						F 100	0.117 (17)		2						2	
						F 200	0.117 (17)		2						2	
						F 500	0.117 (17)		2						2	
						F 100	0.059(8.5)		2						2	
						F 200	0.059(8.5)		2						2	
				6-15		F 500	0.059(8.5)		2						2	
				6-25		E 100	0.241 (35)		2					2		
				6-25		E 200	0.241 (35)		2					2		
				6-25	B	E 500	0.241 (35)		1					1		
20	BARREL COMPRESSION	0.533 (0.021)	30.48 (1.2)	6-15	A	C 100	0.076 (11)		5	5		5			5	

[1] FIRST NUMBER IS CELL SIZE IN 16THS OF AN INCH (1.5875 mm), SECOND NUMBER IS CORE FOIL GAGE IN TEN THOUSANTHS OF AN INCH (0.00254 mm). ALL CORE TYPES ARE SQUARE CELL, CORRUGATED, NON-PERFORATED.

[2] EXPOSURE CYCLE PER FIGURE 3.

[3] SPECIMENS USED TO DEFINE LIMITS OF CAPABILITY -- NO RESIDUAL STRENGTH.

[4] WITH BRAZE FILLETS MACHINED OFF.

[5] WITH BRAZE FILLETS LEFT ON

[6] ZERO DURING THERMAL CYCLING, THEN SUSTAINED 0.591 @ 1033K FOR 7.5 HOURS

[7] ZERO DURING THERMAL CYCLING, THEN SUSTAINED ZERO @ 1033K FOR 7.5 HOURS.

[8] ZERO DURING THERMAL CYCLING, THEN SUSTAINED 0.591 @ 1033K FOR 37.5 HOURS.

Table 3:
Face Tension Creep & Thermal Expansion Tests

AS BRAZED			EXPOSED [1]			THERMAL EXPANSION 76 TO 1360K (-320 TO 2000° F)
CREEP TEST TEMP			CREEP TEST TEMP			
922K 1200F	1033K 1400F	1144K 1600F	922K 1200F	1033K 1400F	1144K 1600F	
2	2	2	2	2	2	2

0.533 mm (0.021 in.) FACE SHEET, FILLETS ON

[1] 100 THERMAL CYCLES (CYCLE E) AT SUSTAINED TENSION OF 172 MPa (25 ksi)

TEST TYPE	TEST METHOD	SPECIMEN SIZE (mm)
FACE TENSION	ASTM E 8	25.4 x 203.2
CORE SHEAR	ASTM C-393	76.2 x 406.4; 76.2 x 203.2; 63.5 x 177.8
EDGEWISE COMPRESSION	ASTM C-364	76.2 x 127.0
FLATWISE TENSION	ASTM C-297	50.8 x 50.8
CORE COMPRESSION	ASTM C-365	76.2 x 76.2
BARREL COMPRESSION	BOEING TEST PROCEDURE	76.2 x 127.0
PEEL	ASTM D-1781	76.2 x 304.8

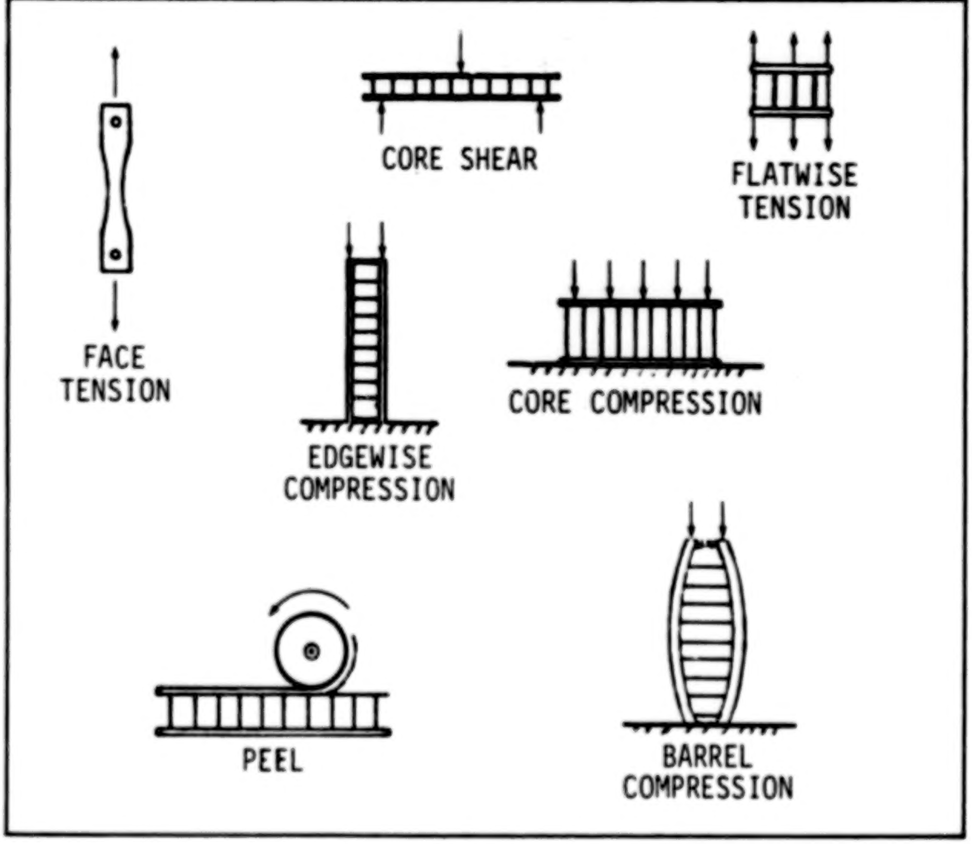

CORE SHEAR
FLATWISE TENSION
FACE TENSION
EDGEWISE COMPRESSION
CORE COMPRESSION
PEEL
BARREL COMPRESSION

Figure 1: Test Methods.

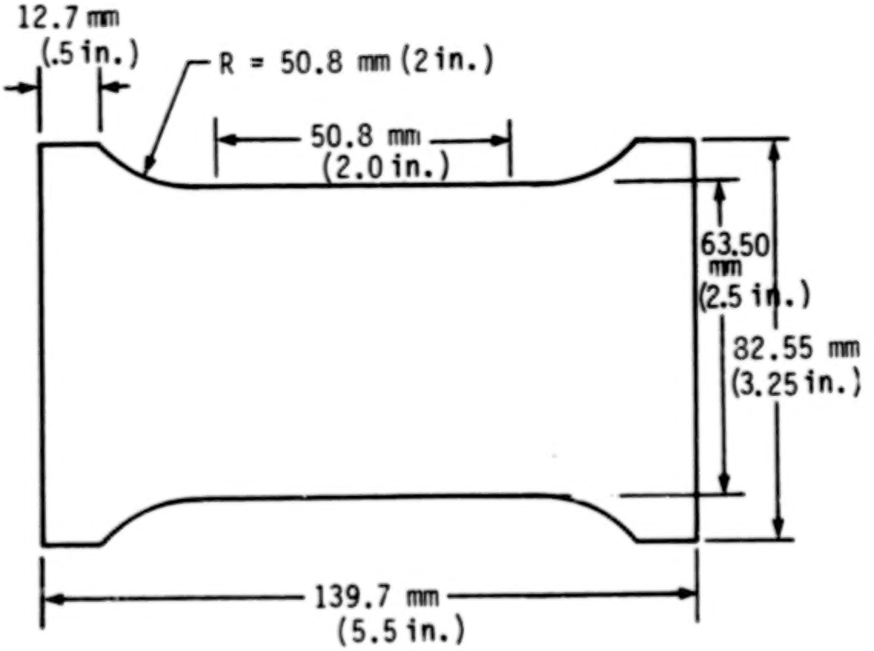

12.7 mm
(.5 in.)
R = 50.8 mm (2 in.)
50.8 mm
(2.0 in.)
63.50 mm
(2.5 in.)
82.55 mm
(3.25 in.)
139.7 mm
(5.5 in.)

Figure 2: Modified Edgewise Compression Specimen.

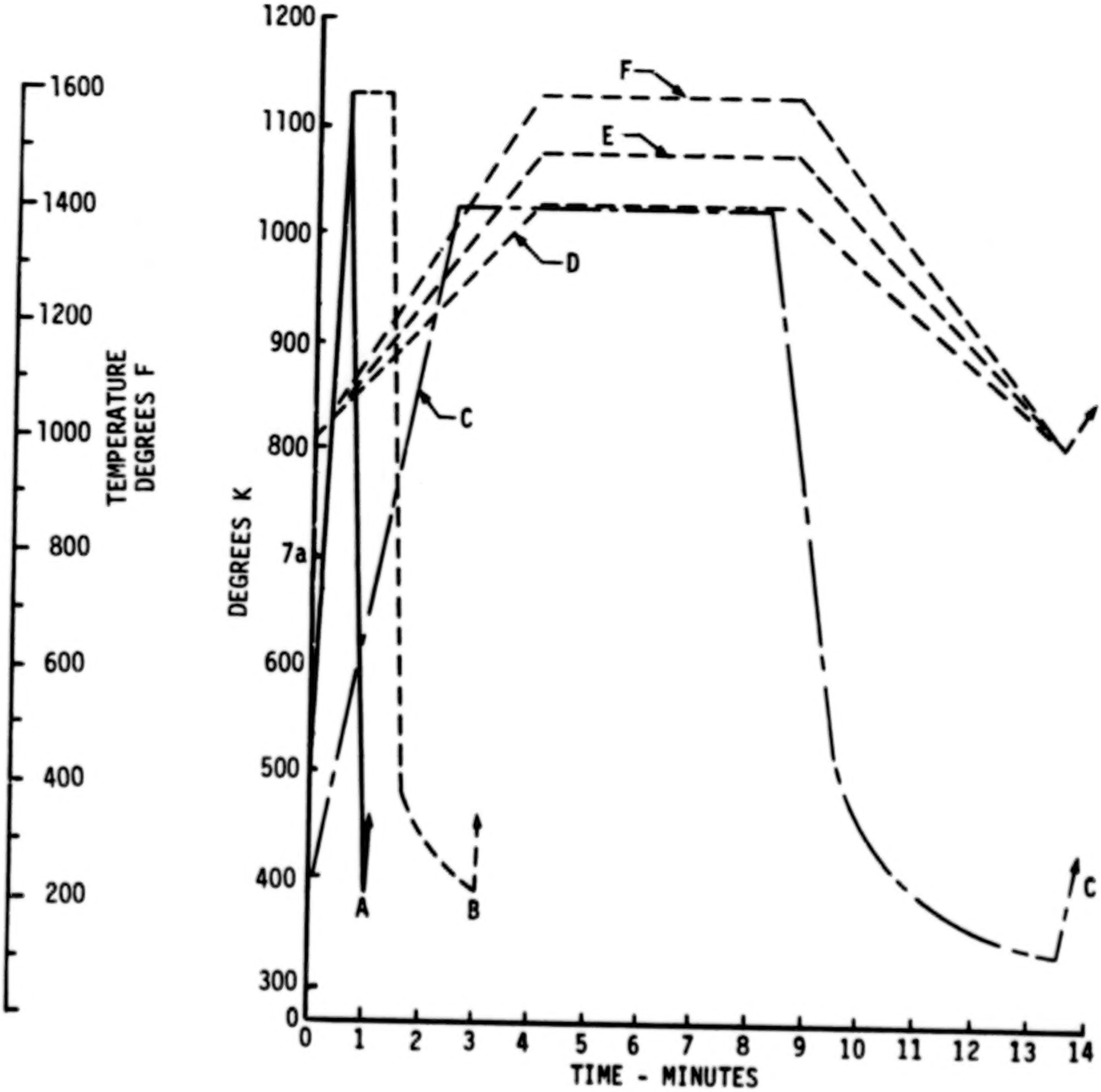


Figure 3: Thermal Exposure Cycles.

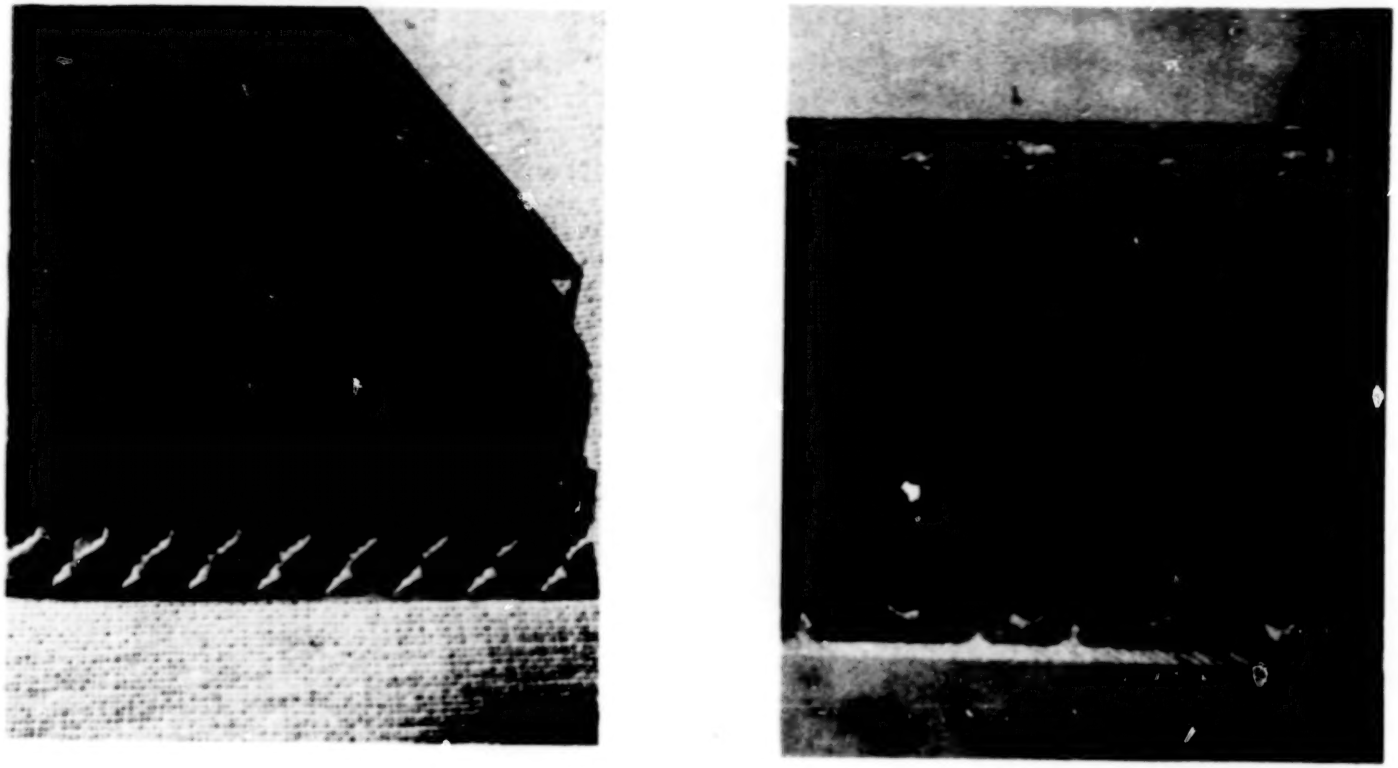


Figure 4: Cross-Sections of Brazed Honeycomb Sandwich.

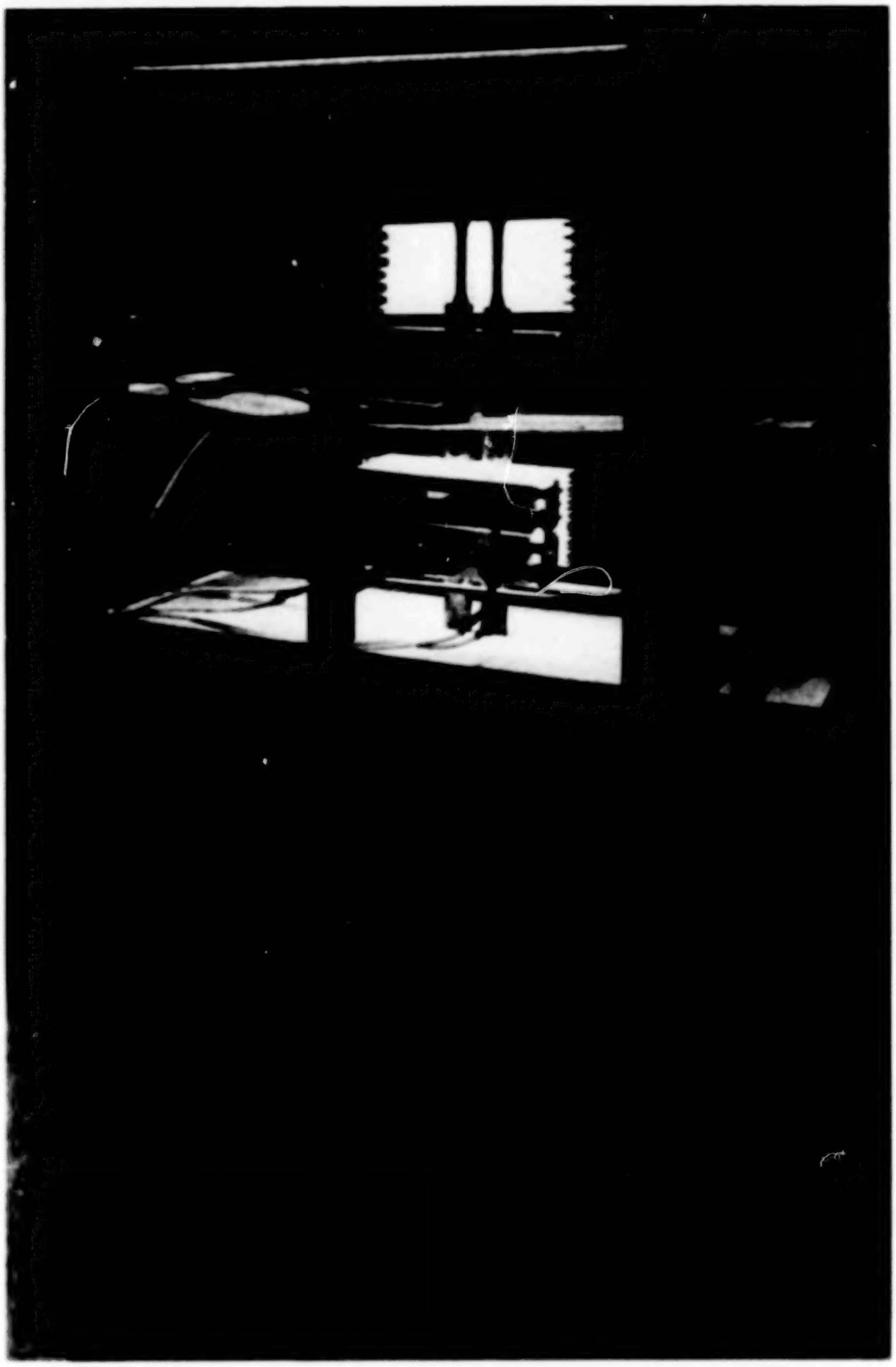


Figure 5: Tensile Specimen Thermal Exposure.

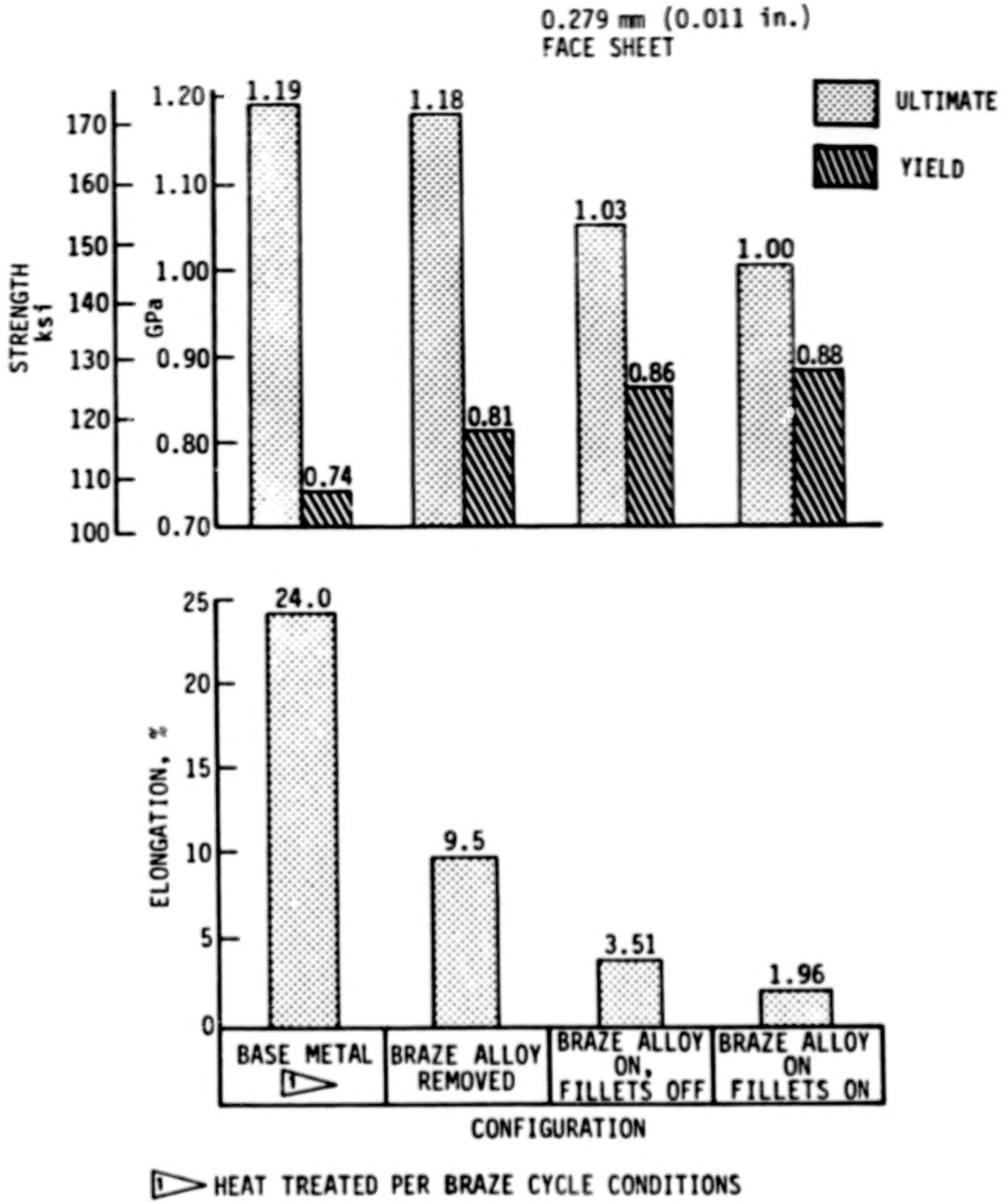


Figure 6
Room Temperature Tensile Properties vs Specimen Configuration.

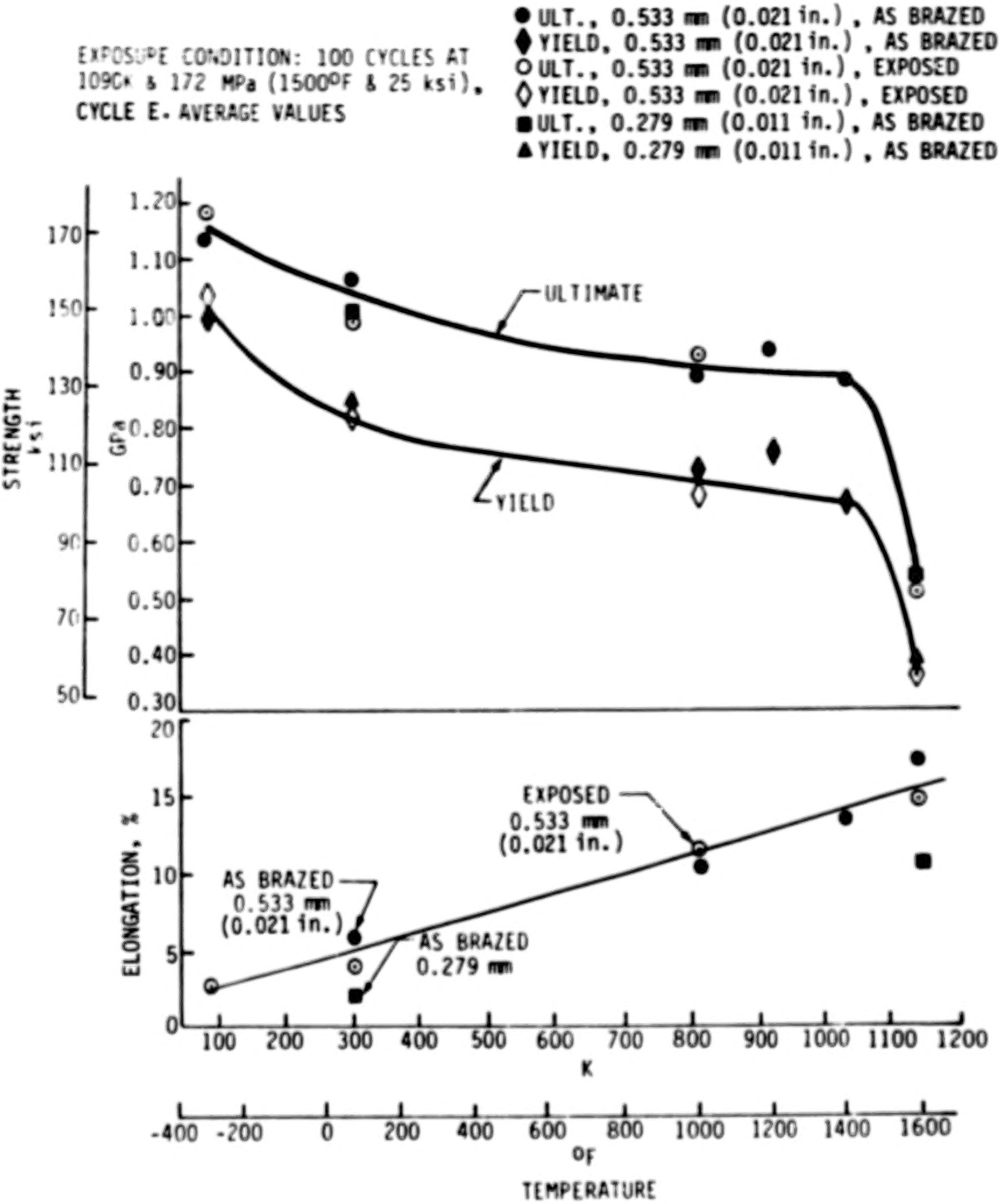


Figure 7

Face Sheet Tension Strength and Elongation vs Temperature

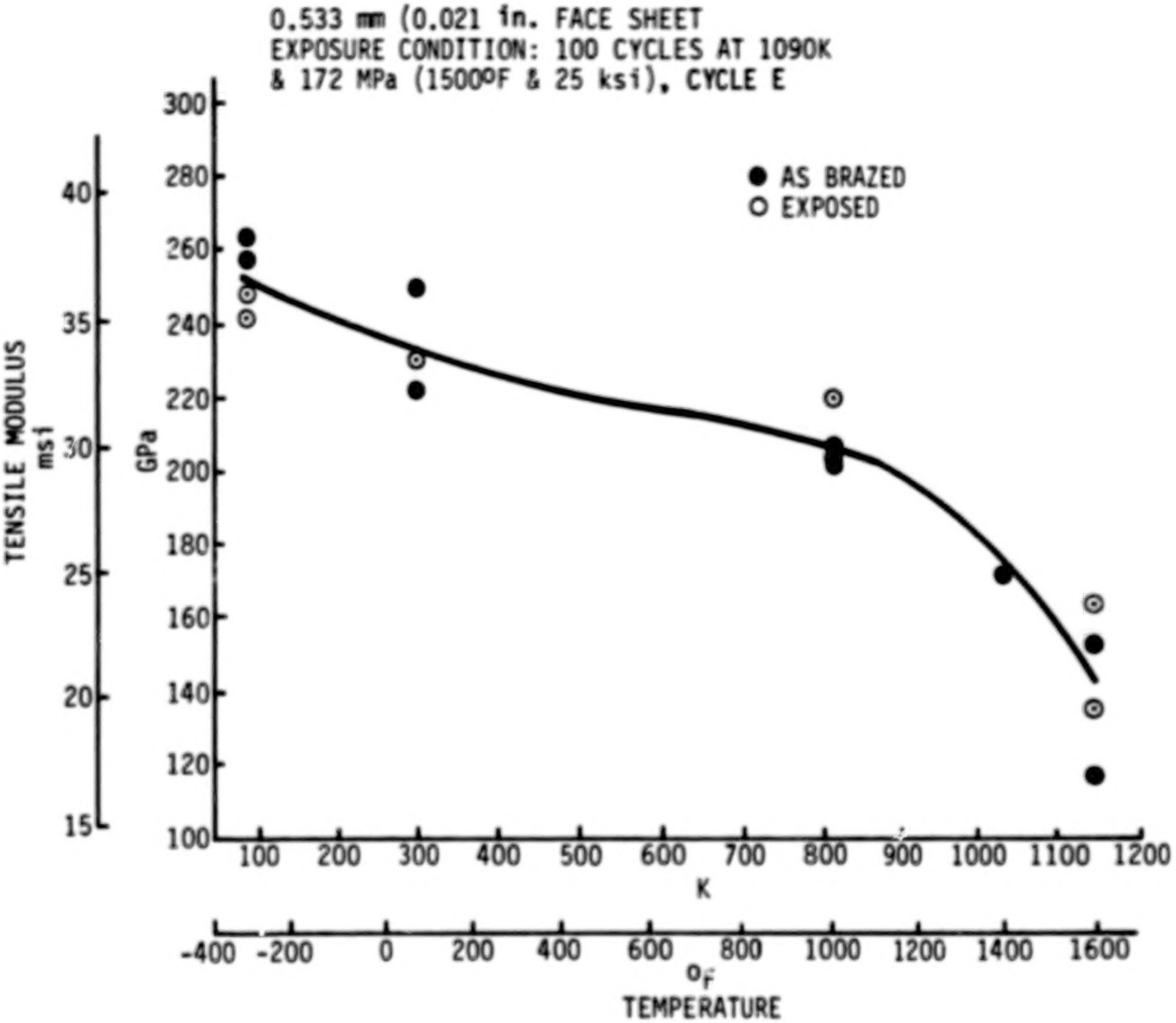


Figure 8: Tensile Modulus vs Temperature.

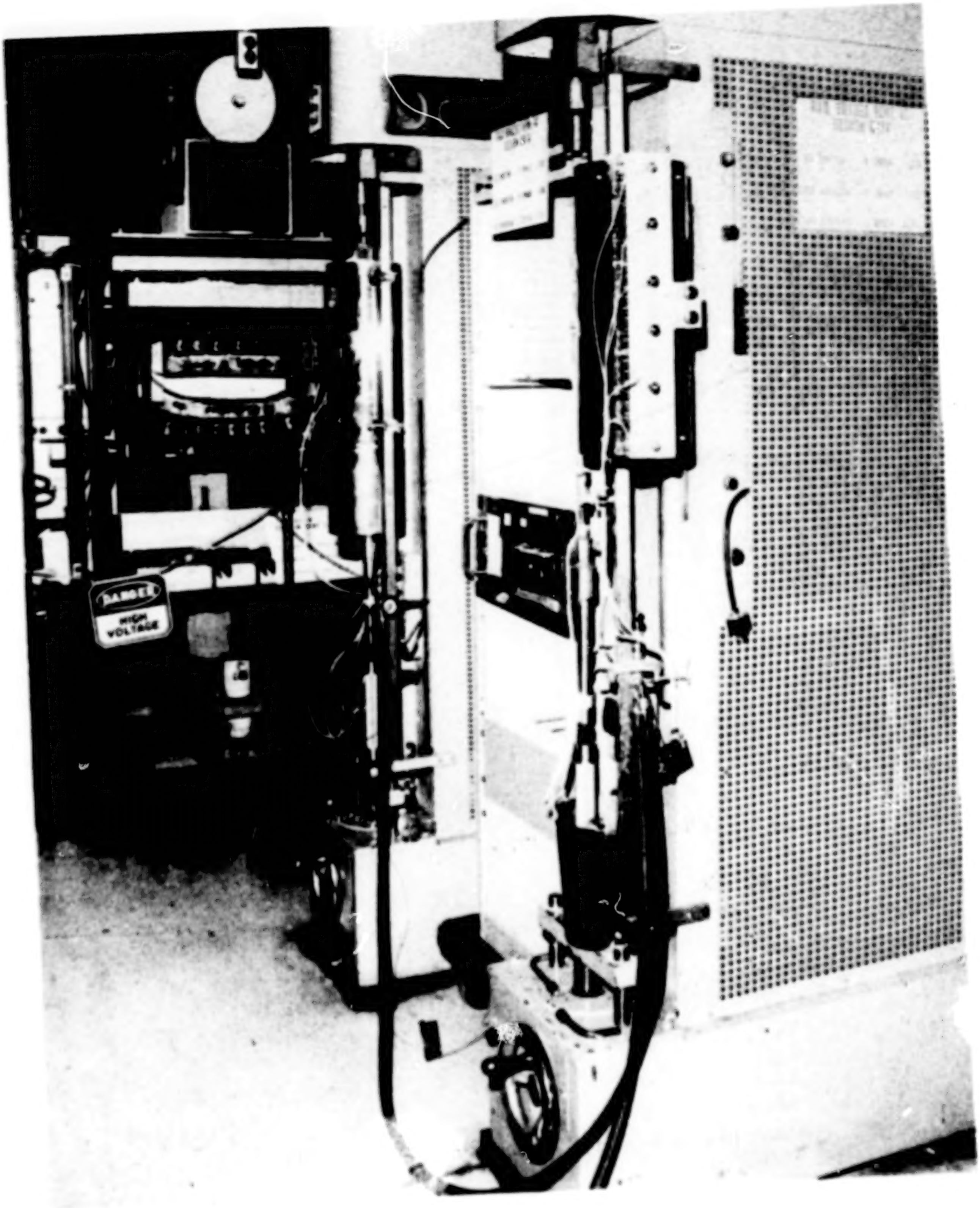

DANGER
HIGH VOLTAGE

Figure 9: Tensile Creep Testing.

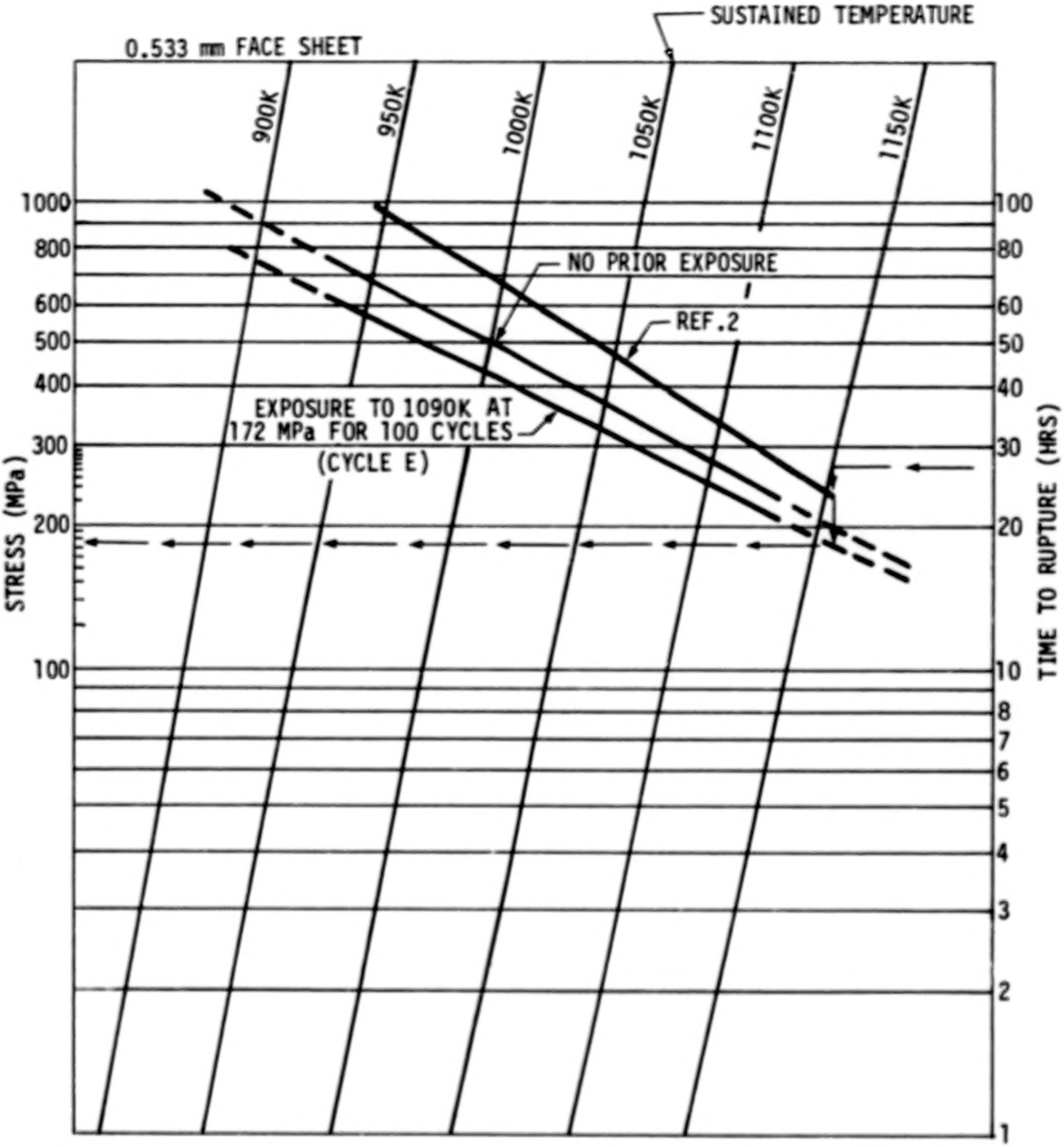


Figure 10A: Tensile Creep Rupture Life Prediction (SI Units).

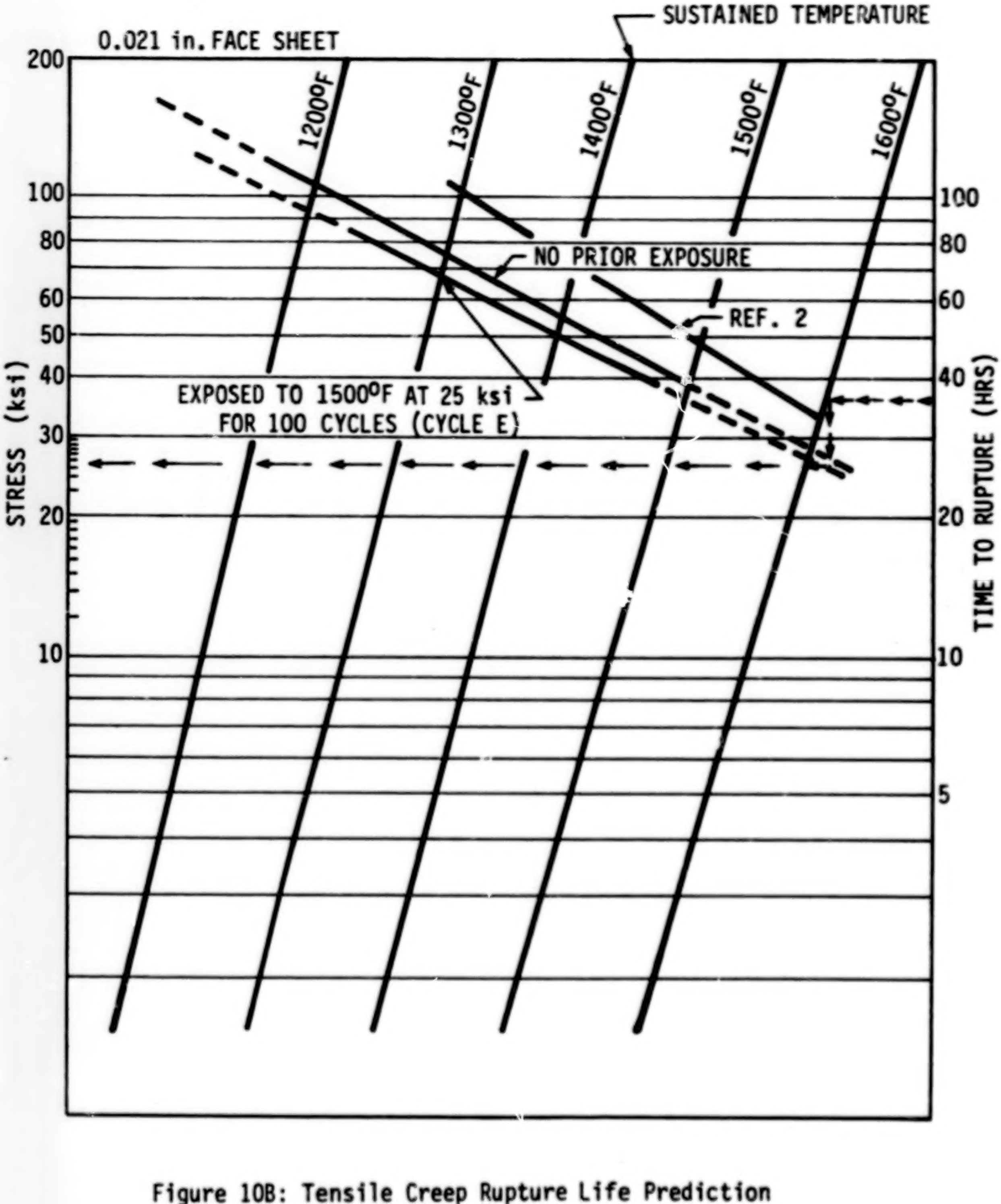
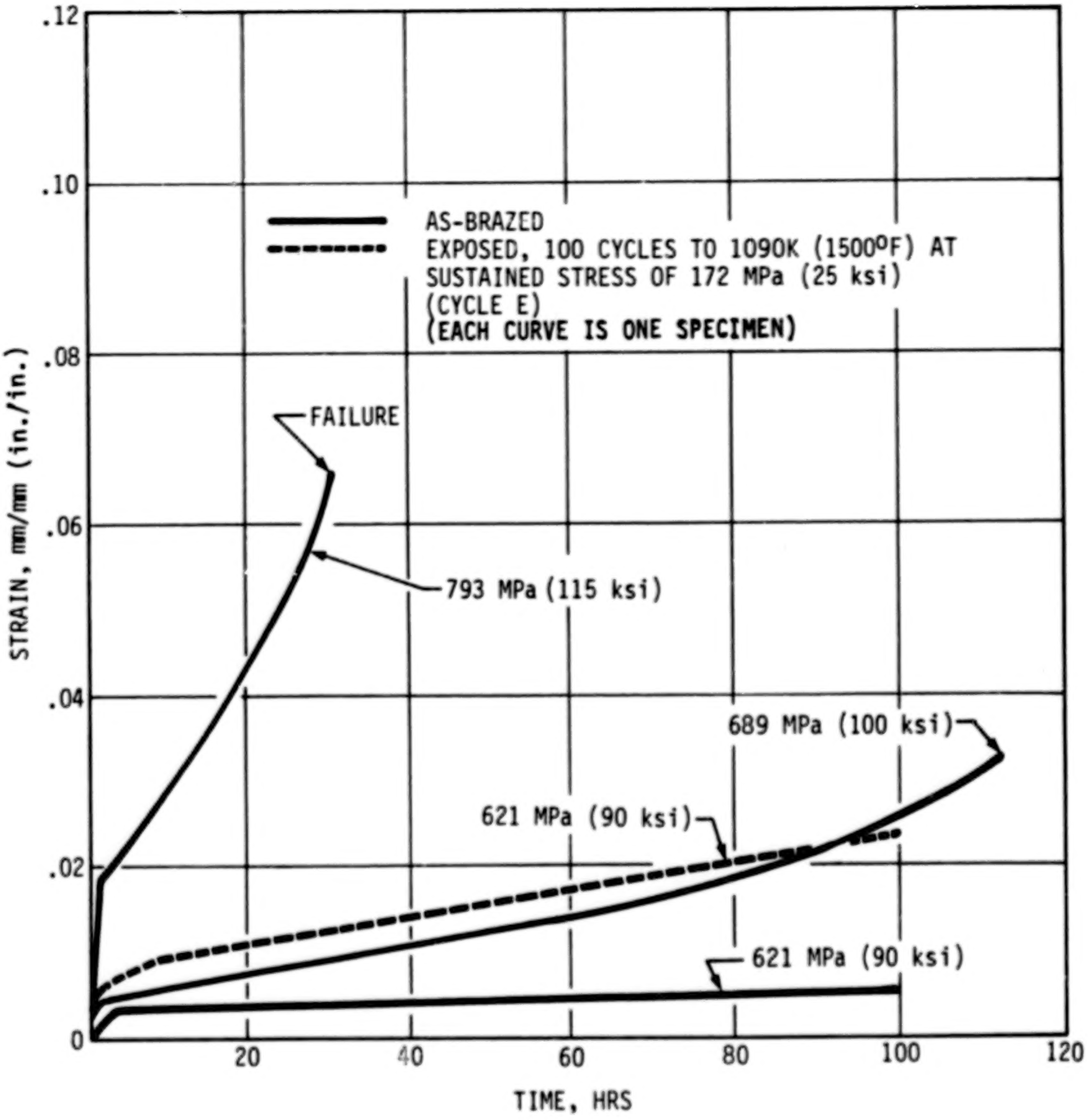
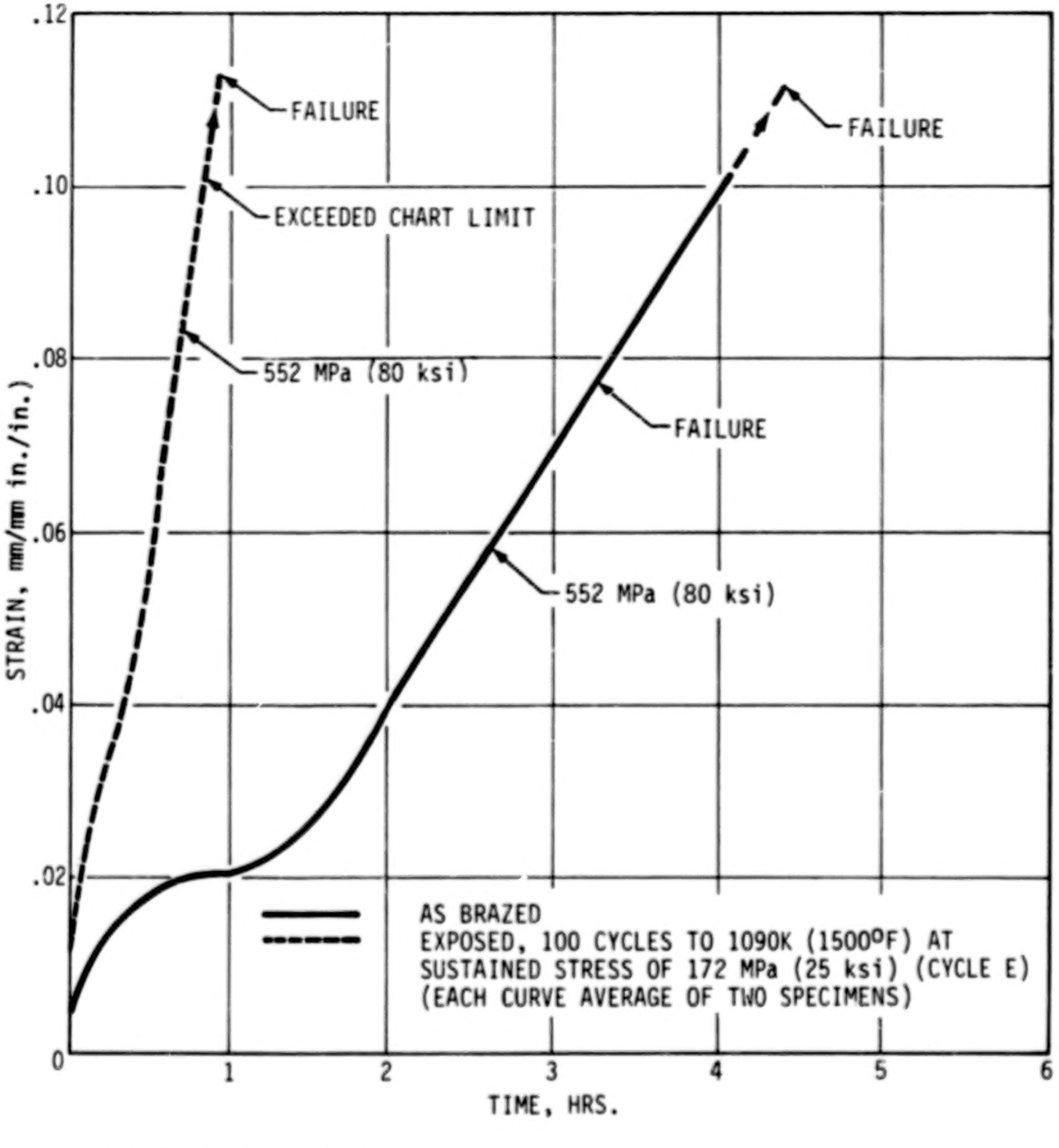


Figure 10B: Tensile Creep Rupture Life Prediction (U.S. Units).



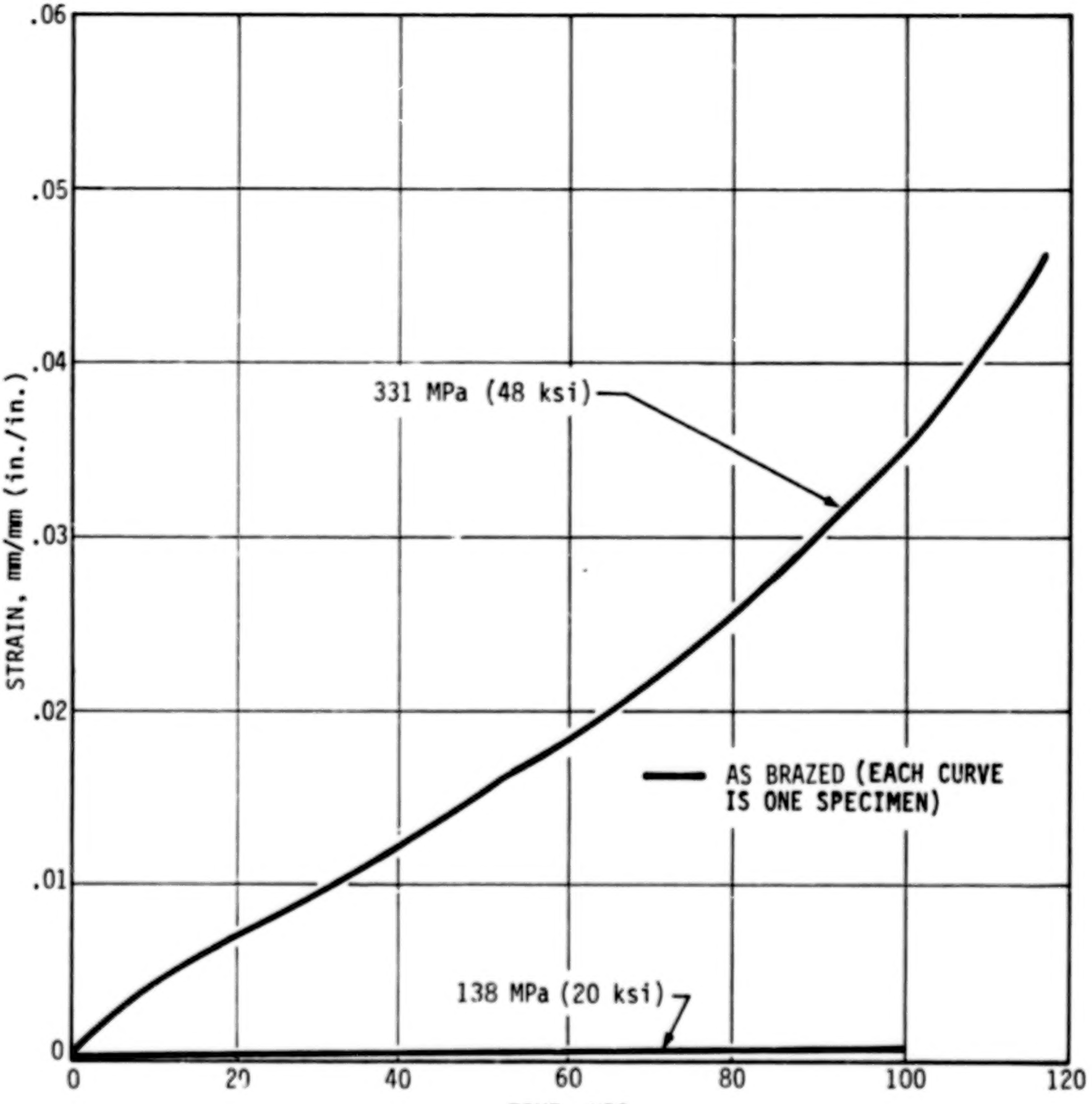
0.533 mm (0.021 in.) FACE SHEET

Figure 11: Tensile Creep Curves at 922K (1200°F).



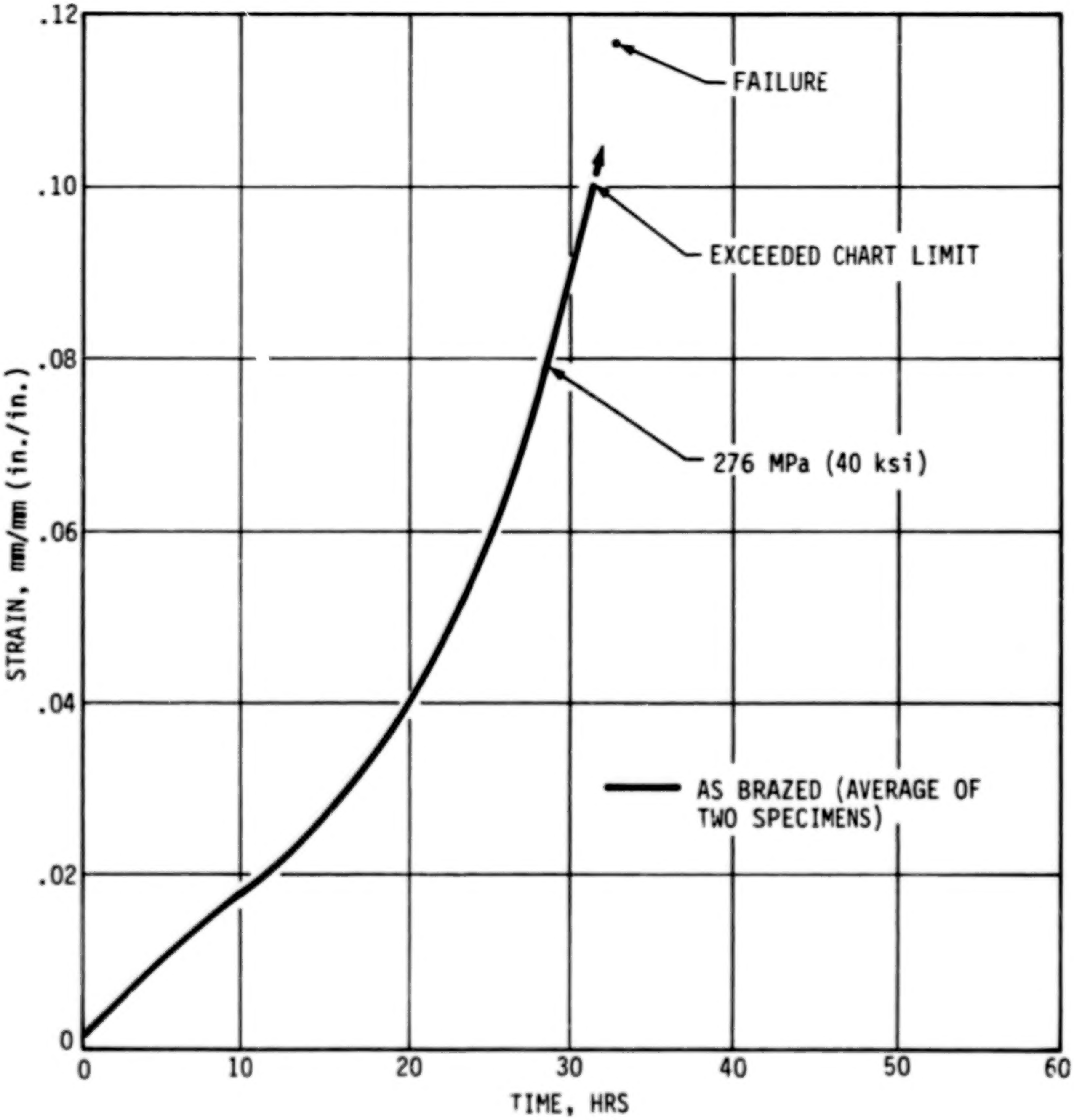
0.533 mm (0.021 in.) FACE SHEET

Figure 12: Tensile Creep Curves at 1033K (1400°F).



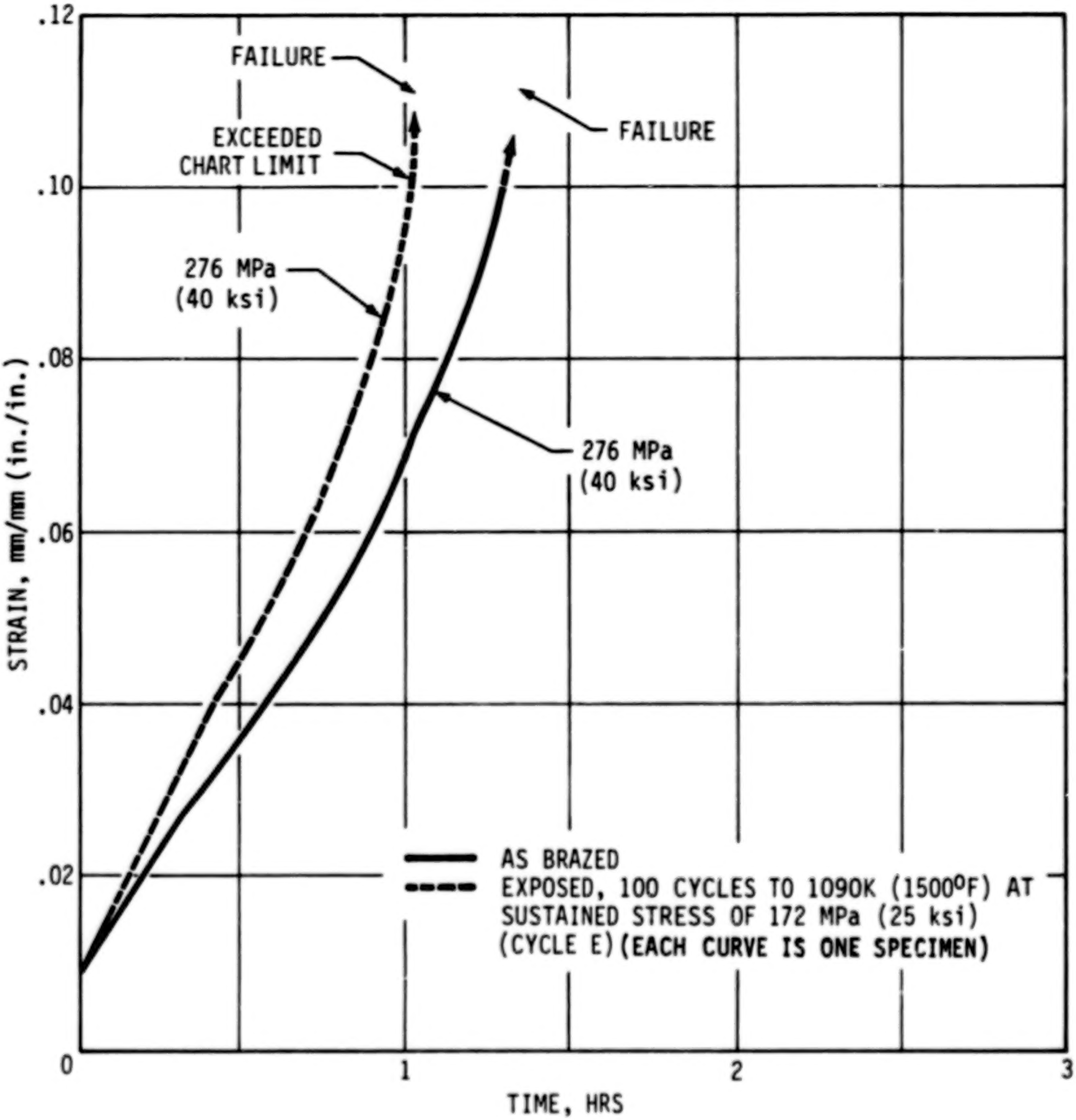
0.533 mm (0.021 in.) FACE SHEET

Figure 13: Tensile Creep Curves at 1033K (1400°F).



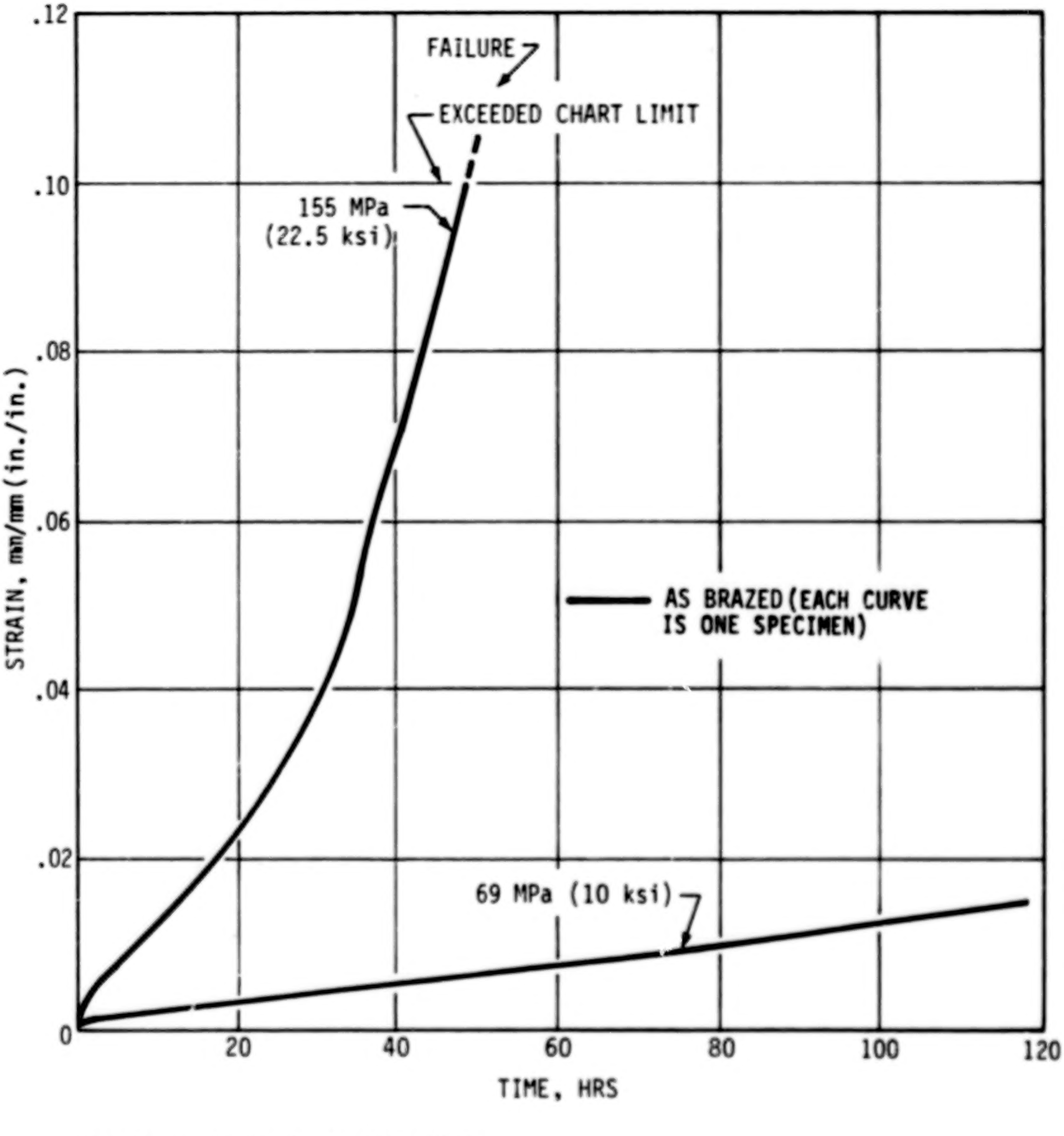
0.533 mm (0.021 in.) FACE SHEET

Figure 14: Tensile Creep Curves at 1090K (1500°F).



'0.533 mm (0.021 in.) FACE SHEET

Figure 15: Tensile Creep Curves at 1144K (1600°F).



0.533 mm (0.021 in.) FACE SHEET

Figure 16: Tensile Creep Curves at 1144K (1600°F).

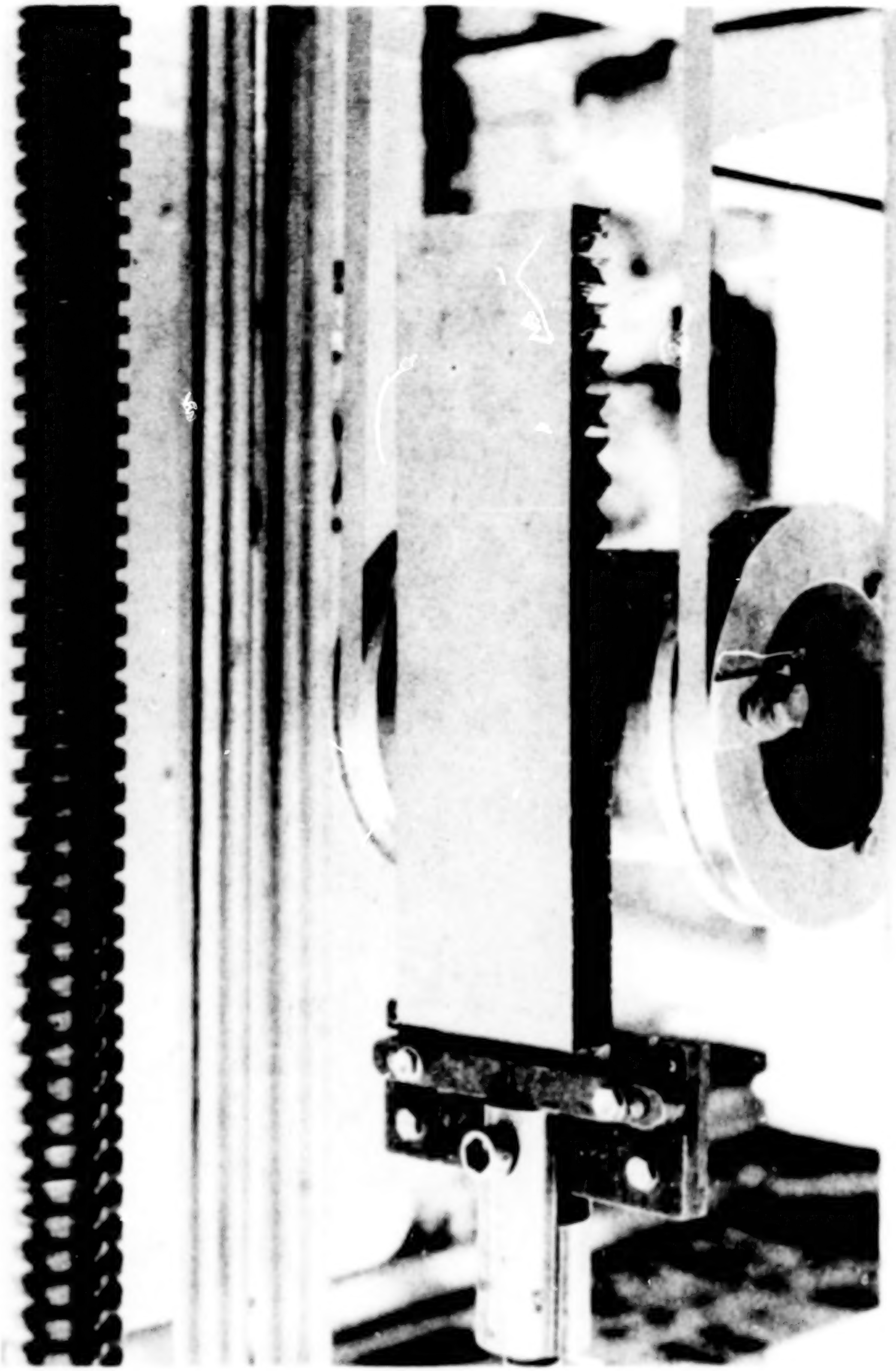


Figure 17: Peel Strength Test.

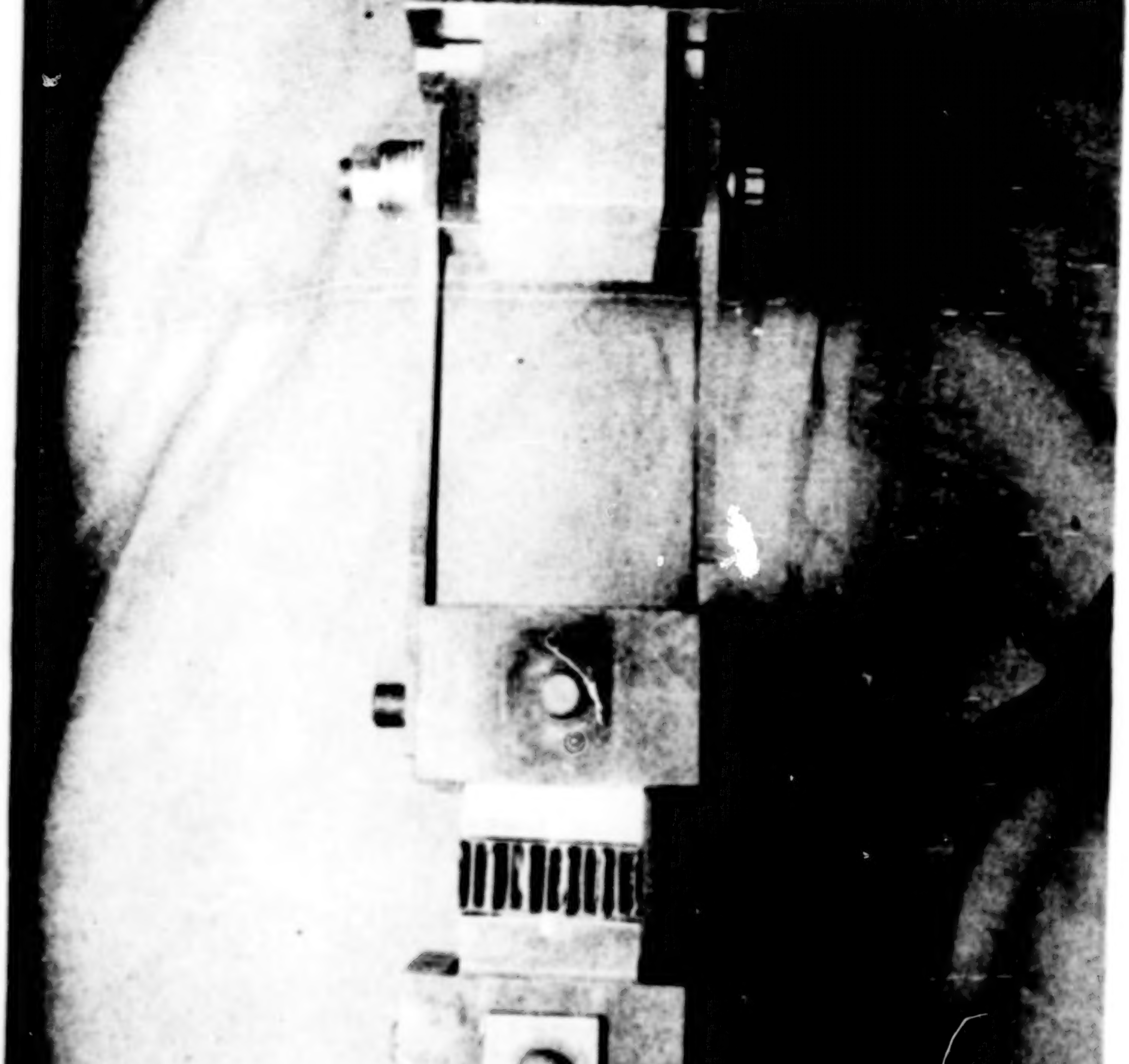


Figure 18: Flatwise Tension Test Setup.

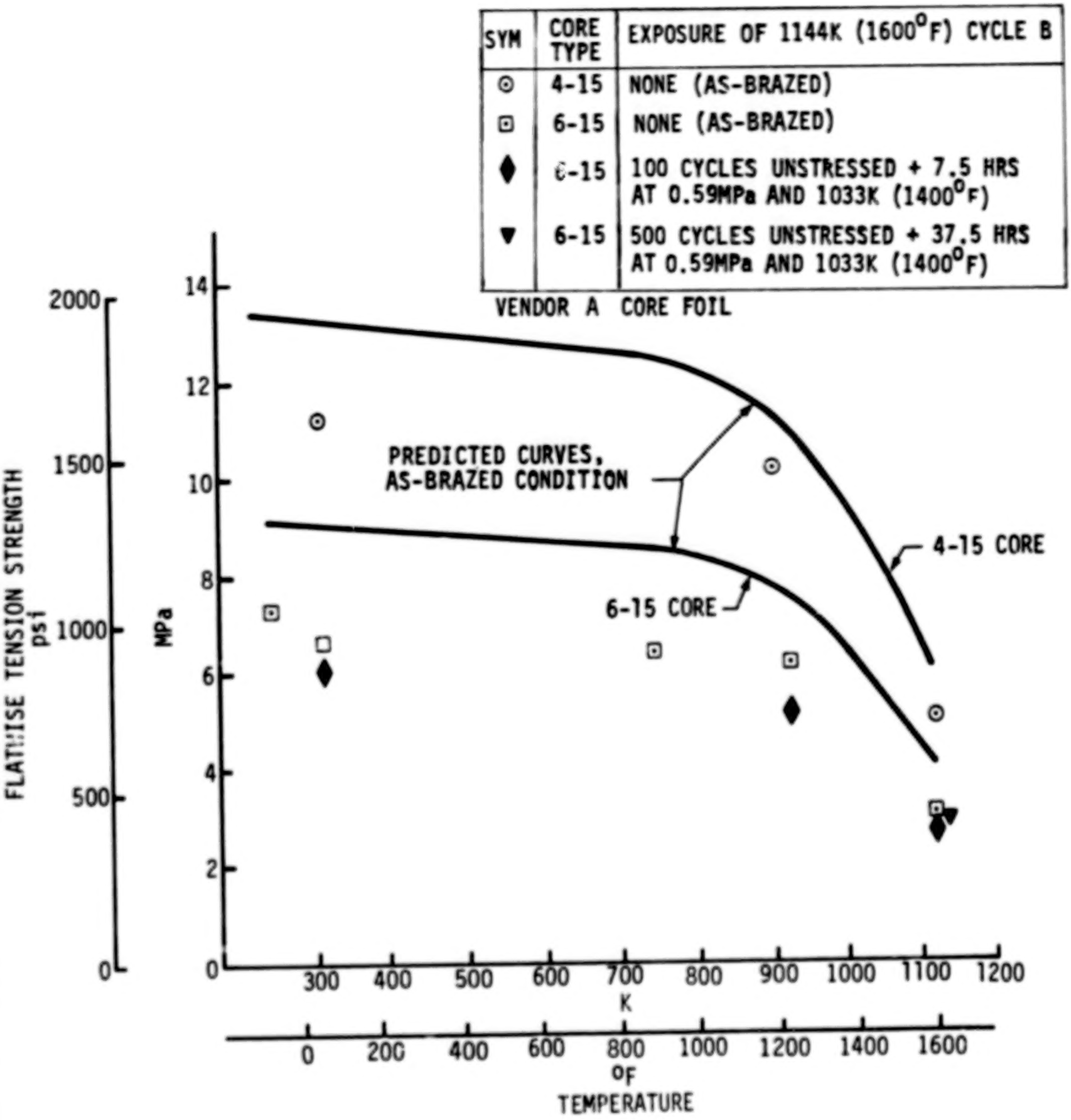


Figure 19

Flatwise Tension Predictions and Test Data vs Temperature Before and After Cyclic Thermal Exposure.

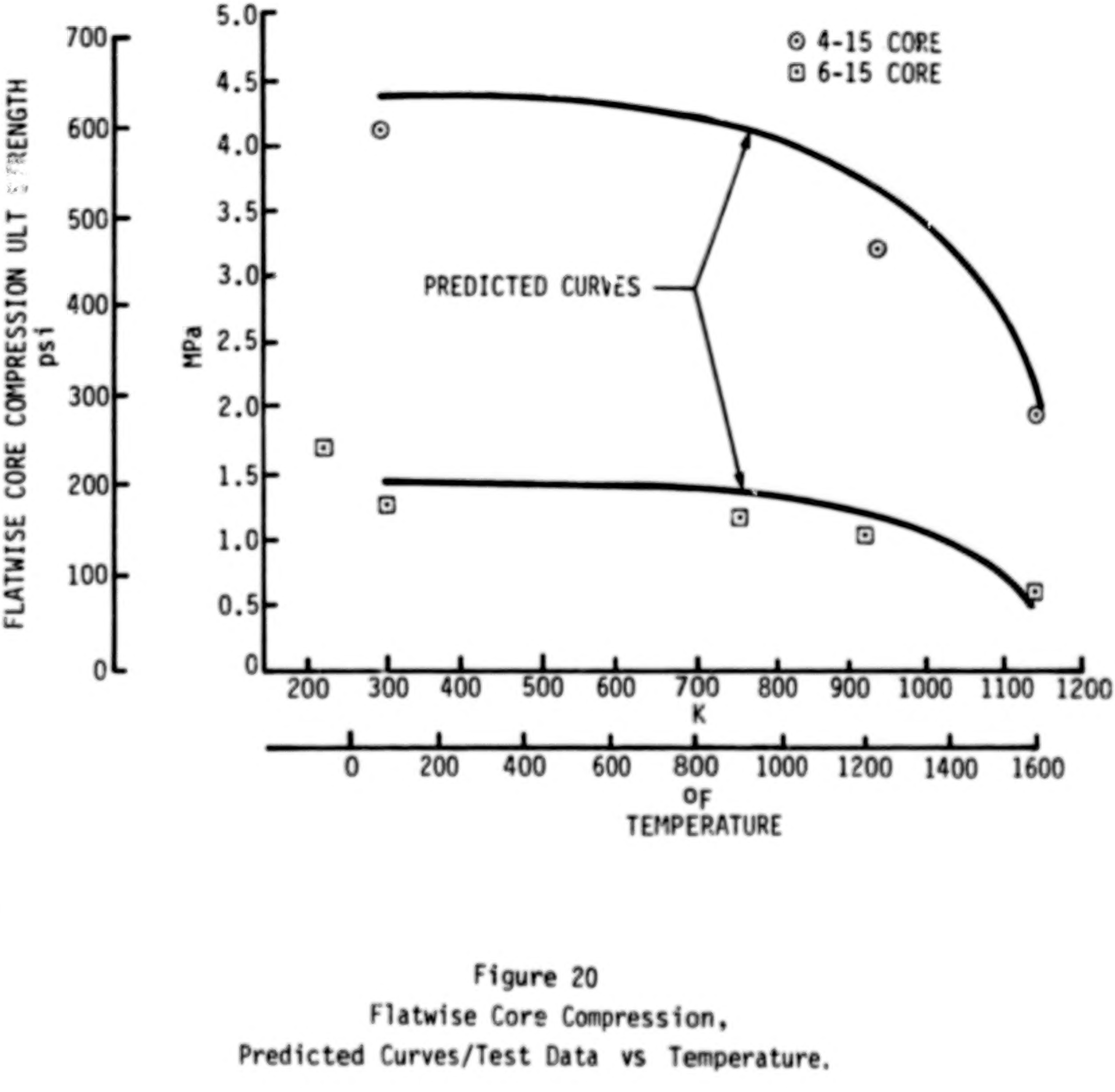


Figure 20
Flatwise Core Compression,
Predicted Curves/Test Data vs Temperature.

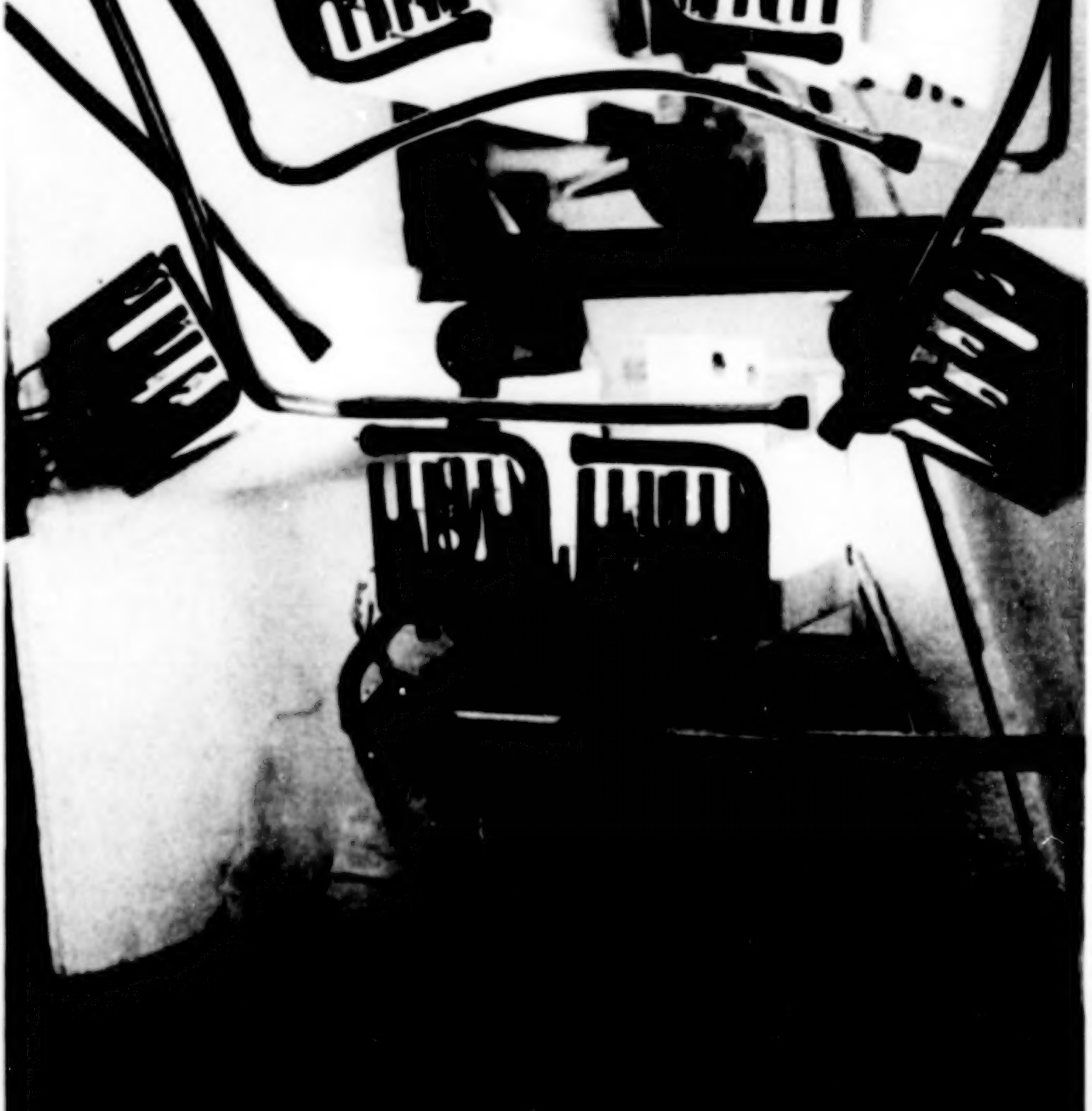


Figure 21: Core Shear Test Setup.

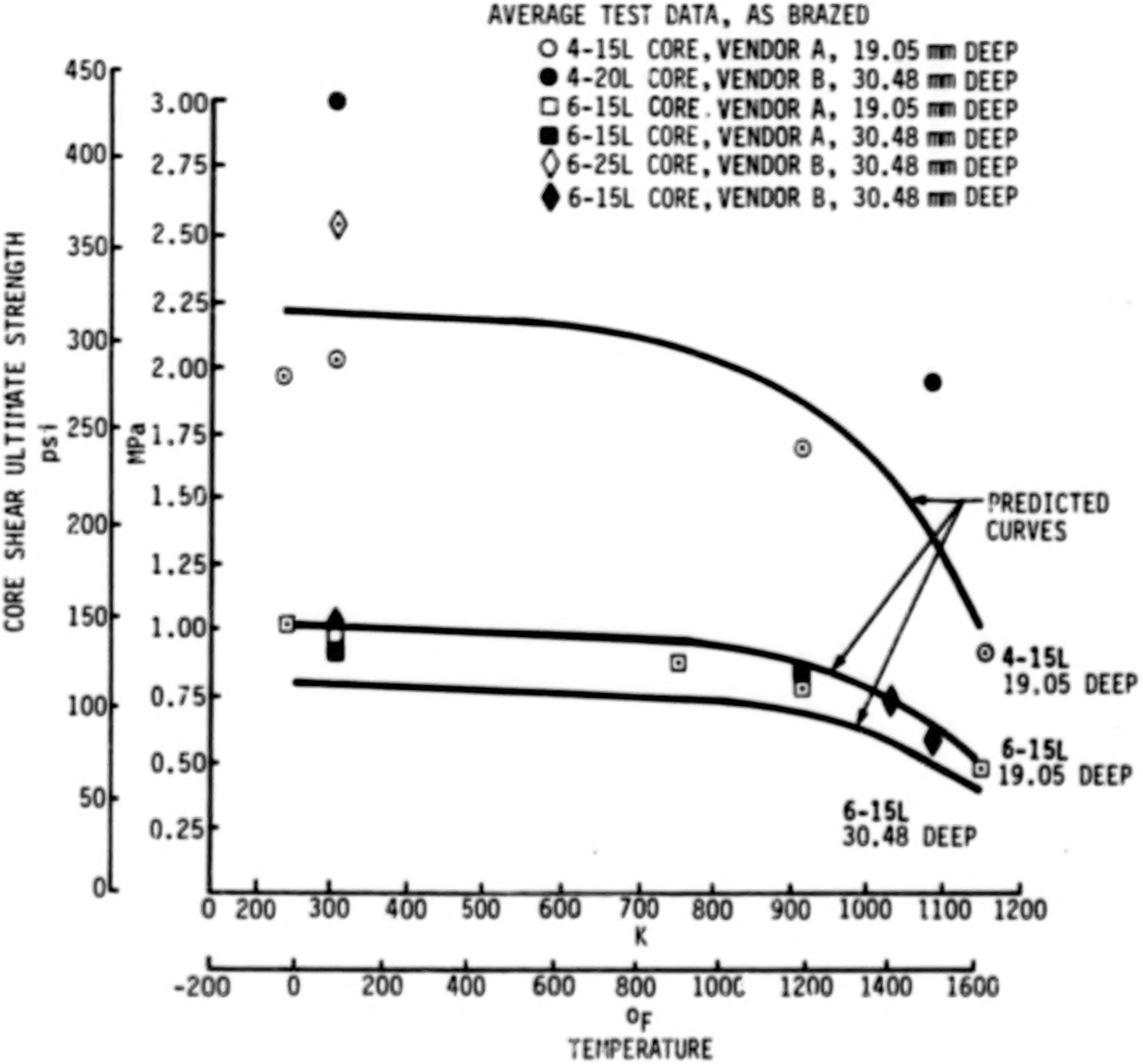


Figure 22

Core Shear Ultimate Strength - Predictions and Test Data vs Temperature.

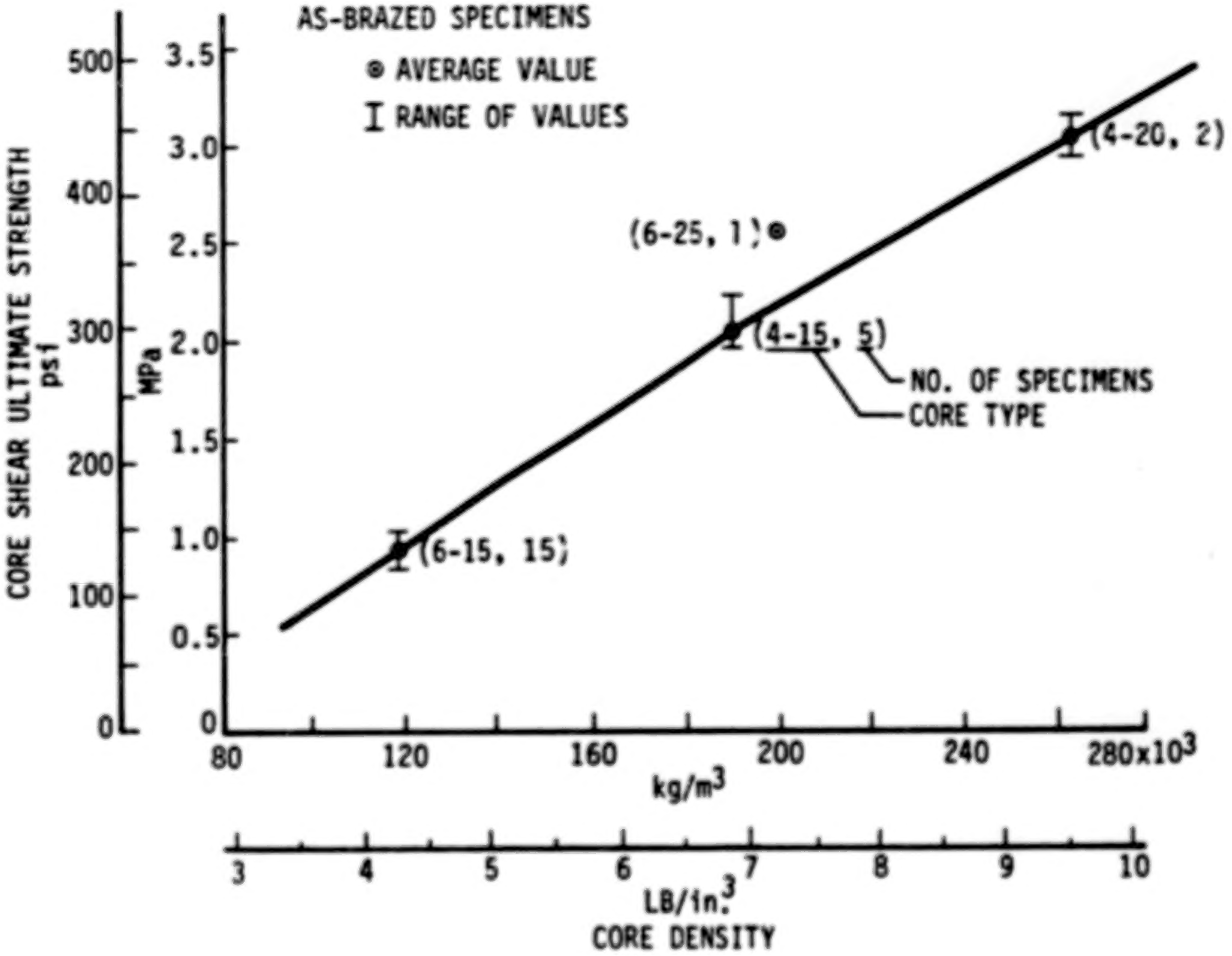


Figure 23

Room Temperature Core Shear Strength vs Core Density.

SYMBOL	CORE TYPE	EXPOSURE STRESS	
		MPa (psi)	% R.T. ULT
●	6-15	.296 (43.0)	31.9
⊡	6-15	.148 (21.5)	15.9

VENDOR "B" FOIL, THERMAL CYCLE "D"
30.48 mm (1.2 in.) CORE DEPTH

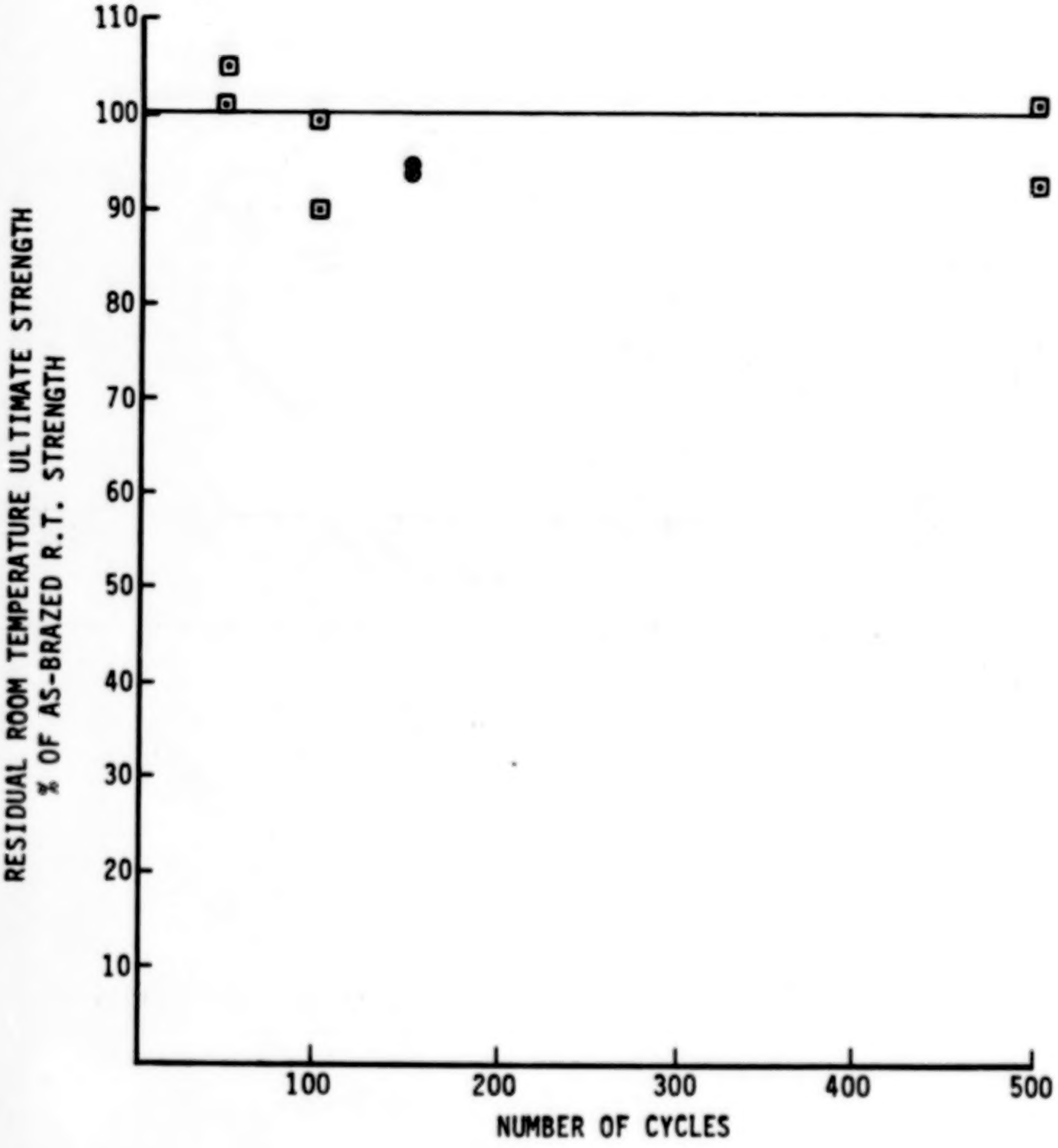


Figure 24: Effect of 1033K (1400°F) Cyclic Exposure on Core Shear Strength at Room Temperature.

SYMBOL	CORE TYPE	EXPOSURE STRESS	
		MPa (psi)	% R.T. ULT
⊙	6-15	0.296(43.0)	31.9
⊡	6-15	0.148(21.5)	15.9

VENDOR "B" FOIL, THERMAL CYCLE "D"
30.48 mm (1.2 in.) CORE DEPTH

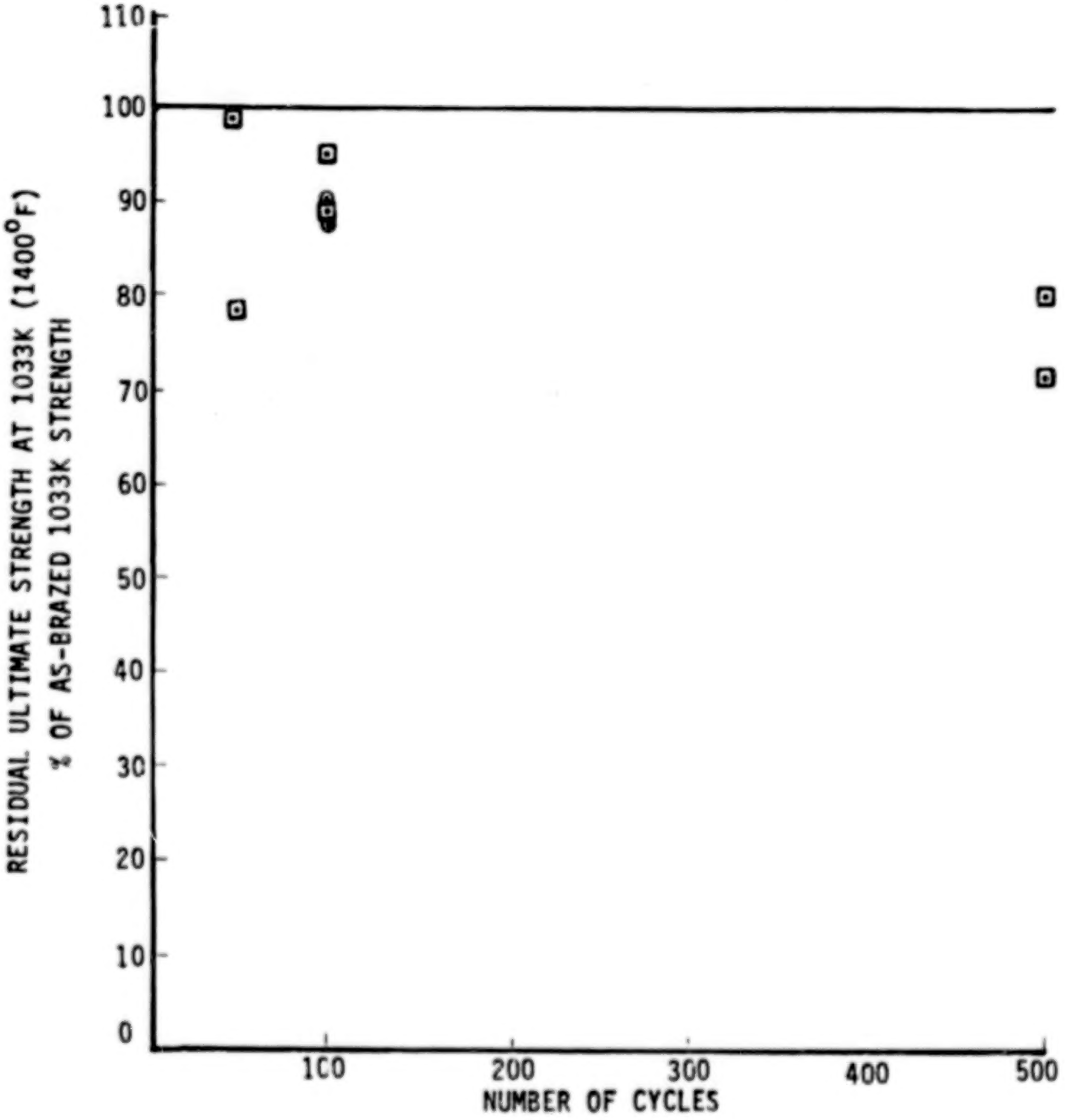


Figure 25
Effect of 1033K (1400°F) Cyclic Exposure on Core Shear Strength at 1033K (1400°F).

SYMBOL	CORE TYPE	EXPOSURE STRESS	
		MPa (psi)	% R.T. ULT
●	6-15	0.069 (10)	7.4
⊡	6-15	0.138 (20)	14.8
•	4-20	0.276 (40)	9.1
■	6-25	0.228 (33)	8.9

VENDOR "B" FOIL, THERMAL CYCLE "E"
30.48 mm (1.2 in.) CORE DEPTH

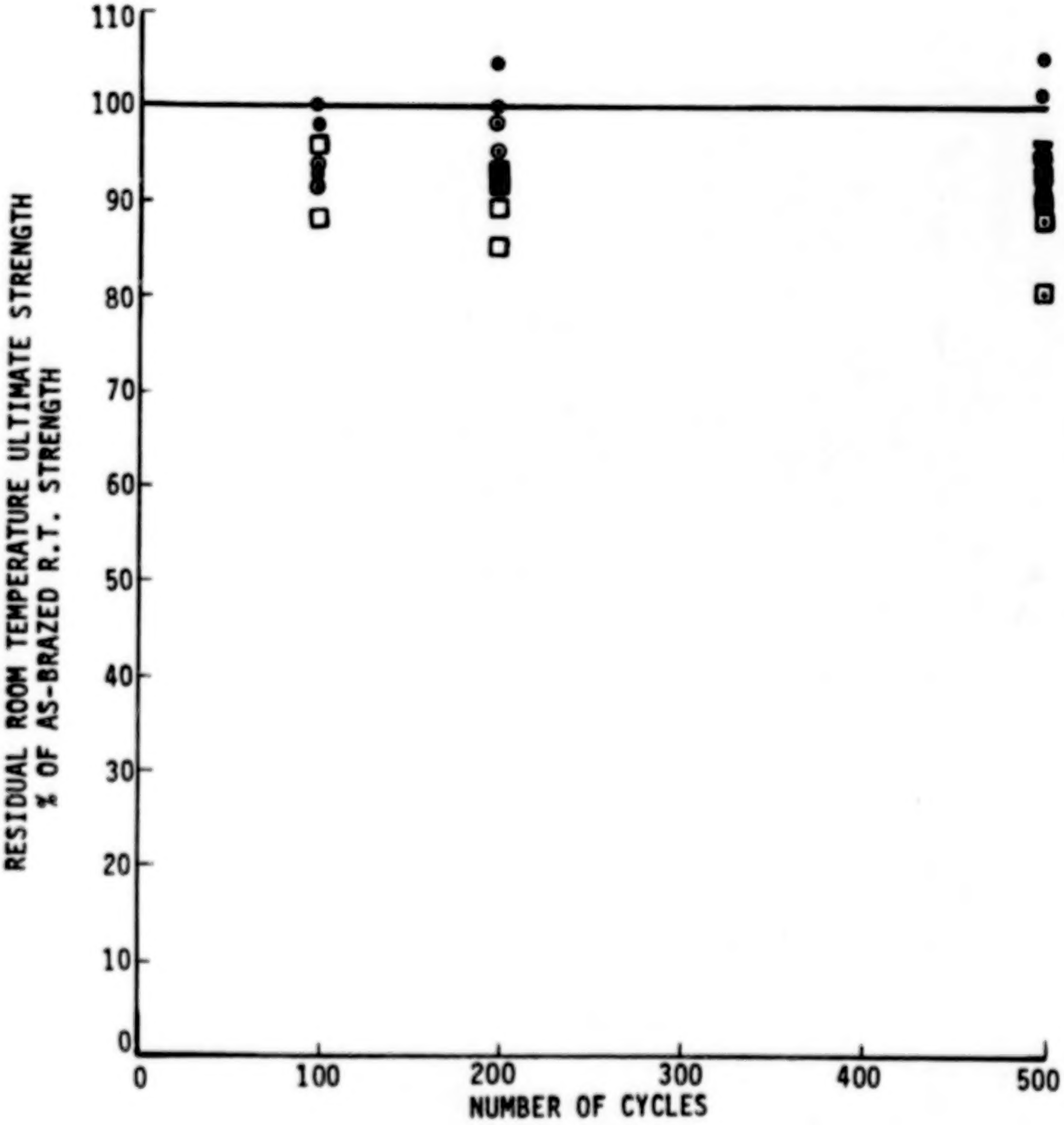


Figure 26
Effect of 1090K (1500°F) Cyclic Exposure on Core Shear Strength at Room Temperature.

SYMBOL	CORE TYPE	EXPOSURE STRESS	
		MPa (psi)	% R.T. ULT.
◉	6-15	0.069 (10)	7.4
⊡	6-15	0.138 (20)	14.8
●	4-20	0.276 (40)	9.1

VENDOR "B" FOIL, THERMAL CYCLE "E"
30.48 mm (1.2 in.) CORE DEPTH

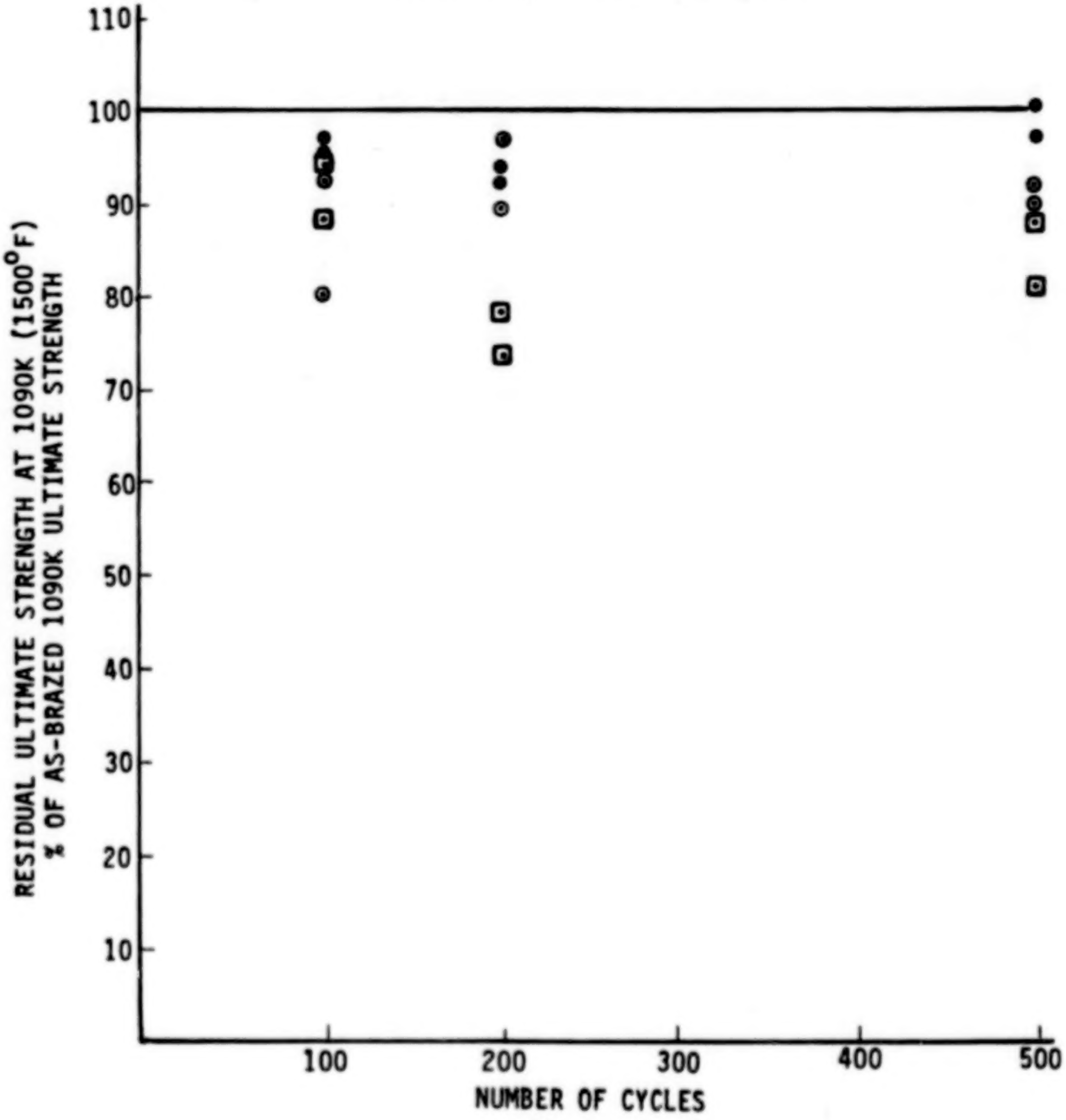
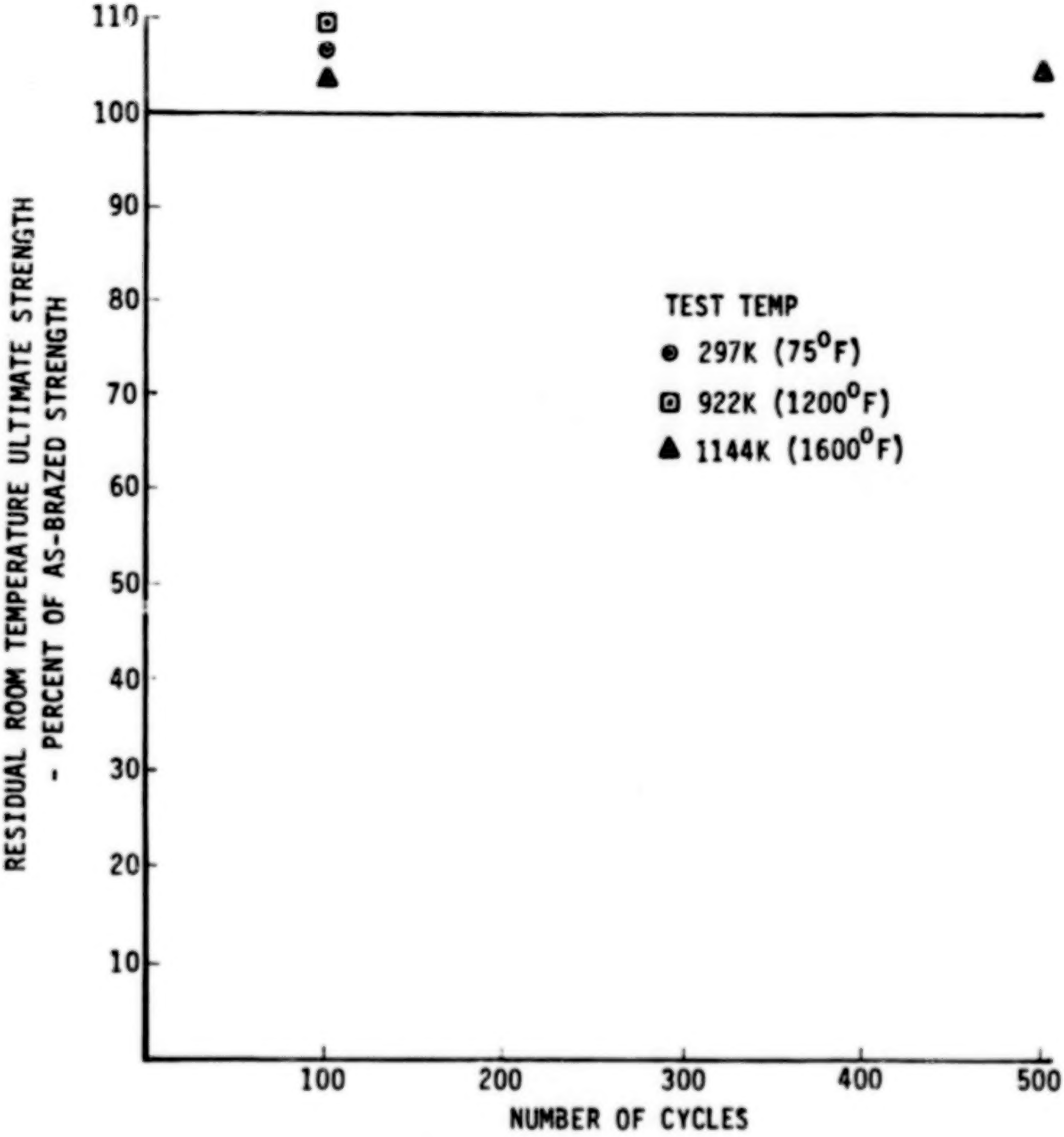


Figure 27

Effect of 1090K (1500°F) Cyclic Exposure on Core Shear Strength at 1090K (1500°F).



6-15 CORE, VENDOR A, 19.05 mm (1.2 in.), EXPOSED TO THERMAL CYCLE "C", 1033K (1400°F) AT 0.089 MPa (12.9 psi)

Figure 28: Effect of 1033K (1400°F) Exposure on Core Shear Strength.

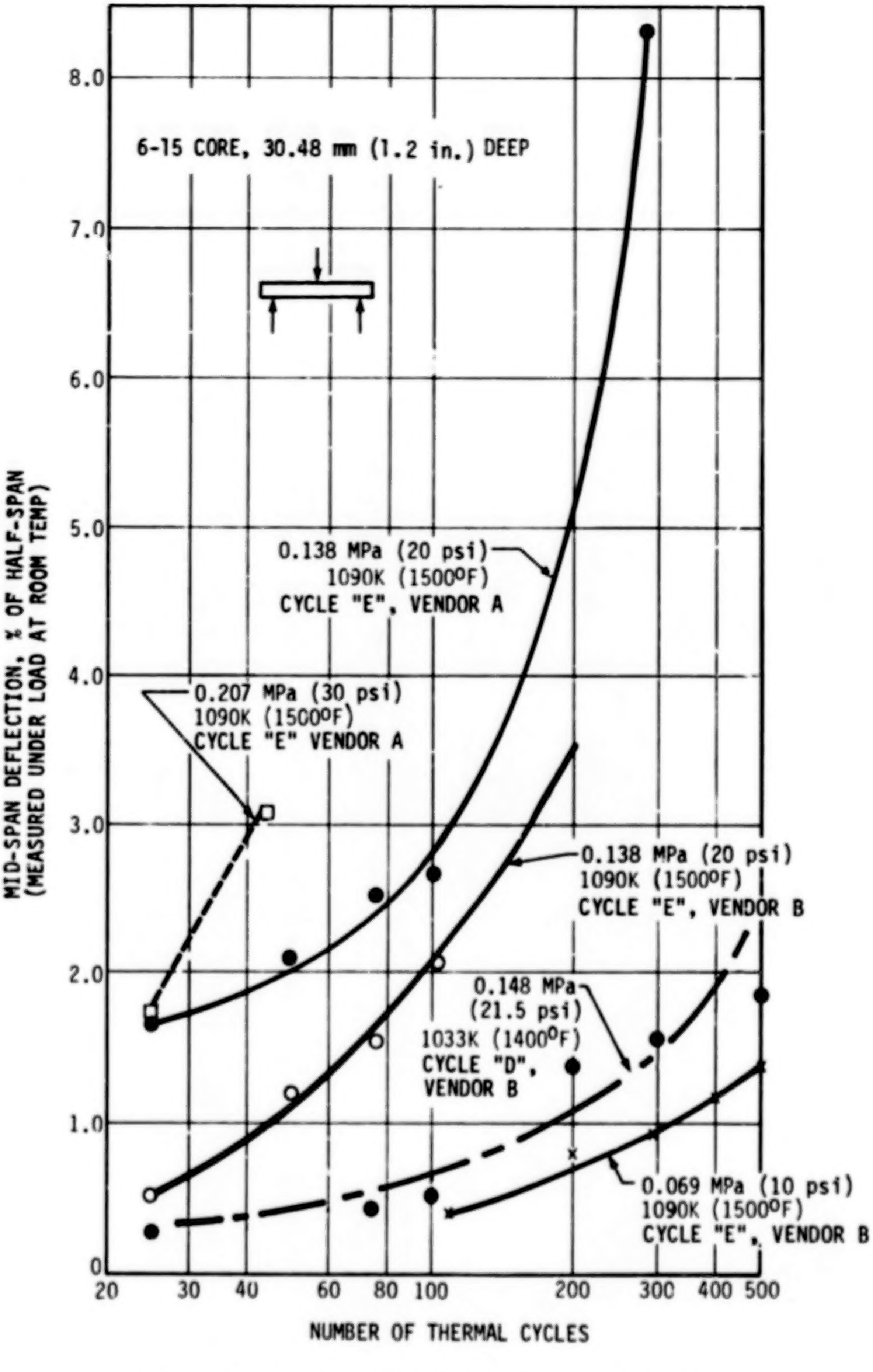
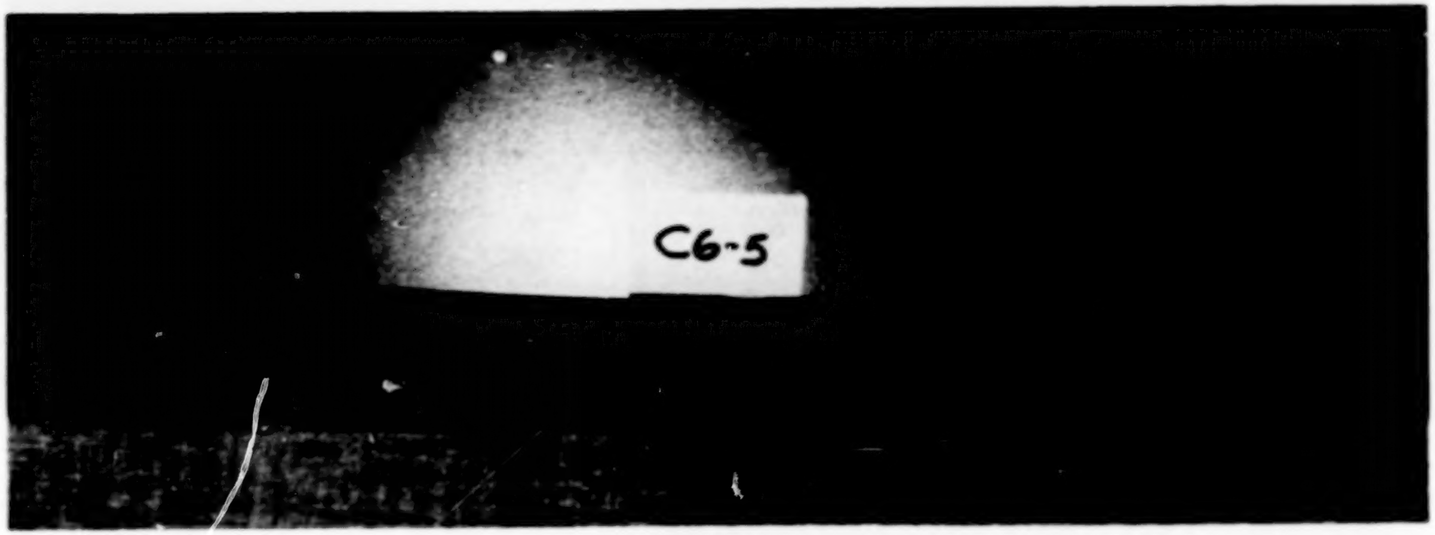
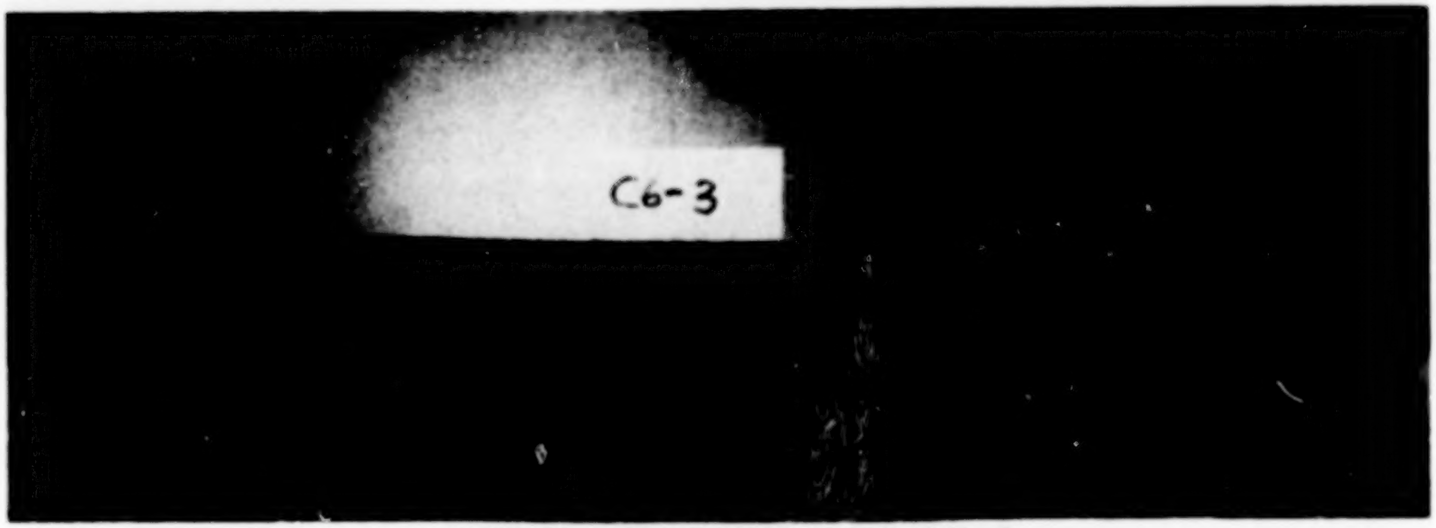


Figure 29: Typical Shear Creep vs Thermal Cycles.



EXPOSURE: 1090K AT 0.14 MPa (1500°F AT 20 psi)
FOR 500 CYCLES (CYCLE E)



EXPOSURE: 1090K AT 0.14 MPa (1500°F AT 20 psi)
FOR 200 CYCLES (CYCLE E)

Figure 30: Core Shear Specimen After Thermal Exposure.

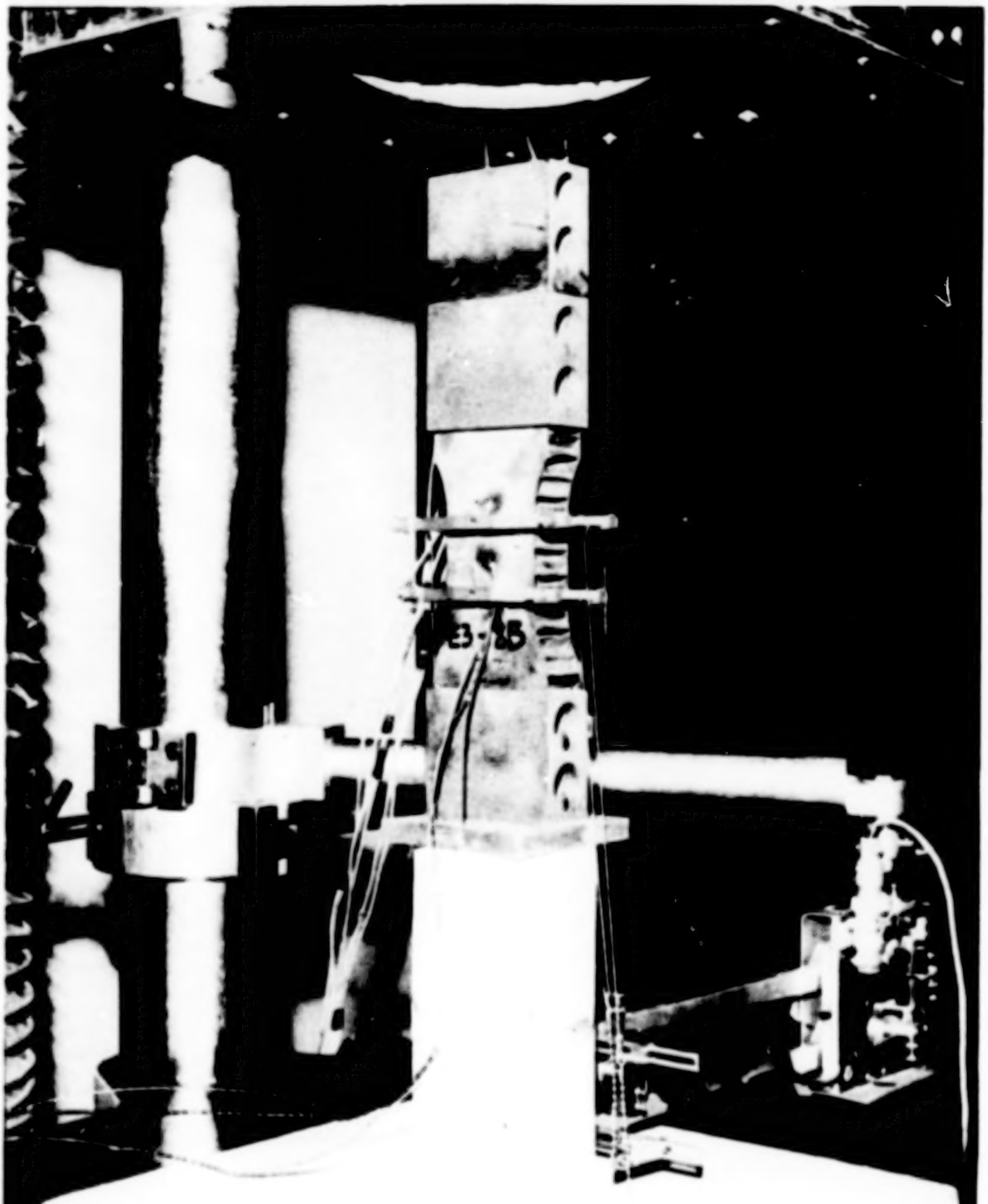


Figure 31: Edgewise Compression Test Setup.

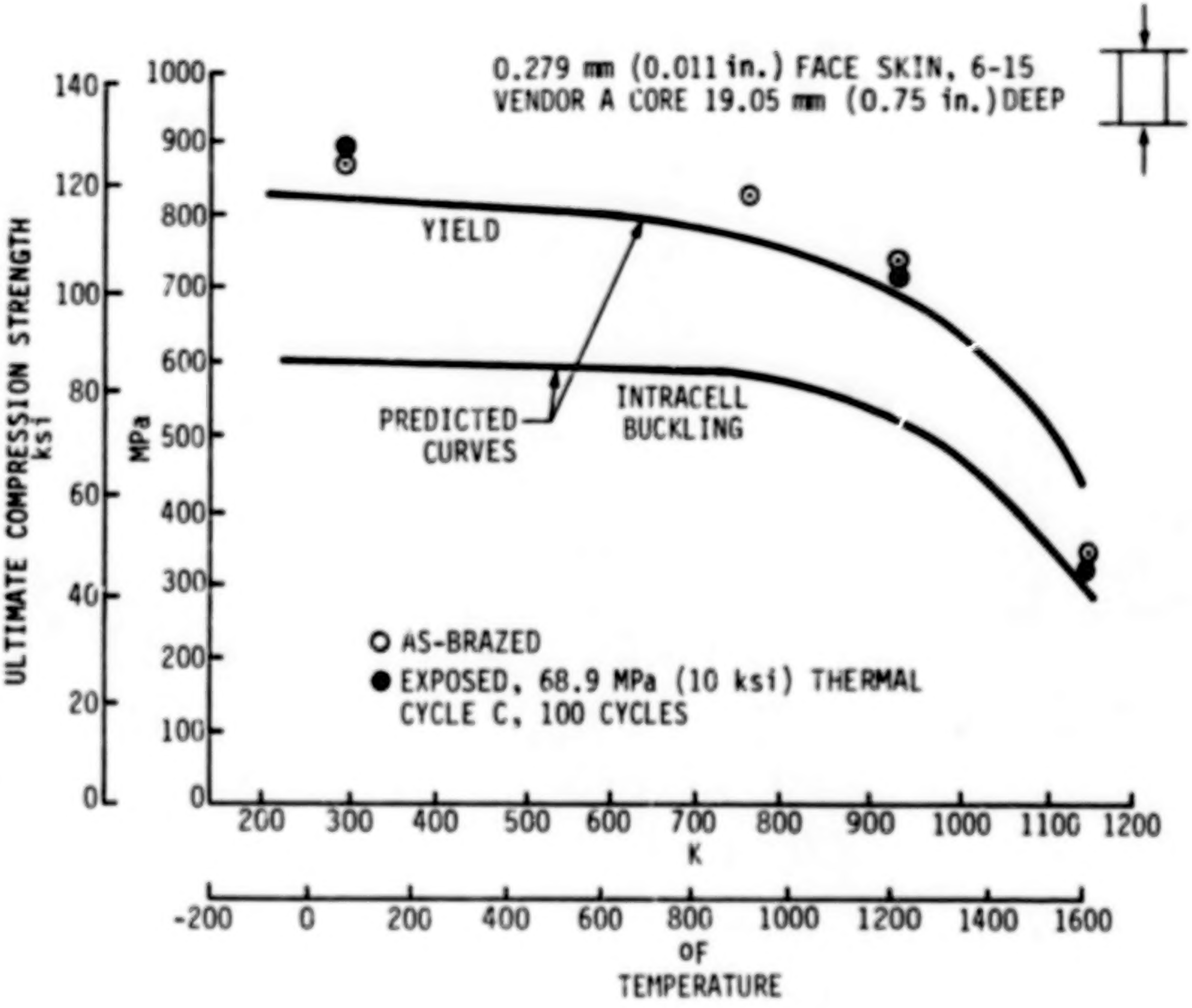


Figure 32
Edgewise Compression Strength vs Temperature.

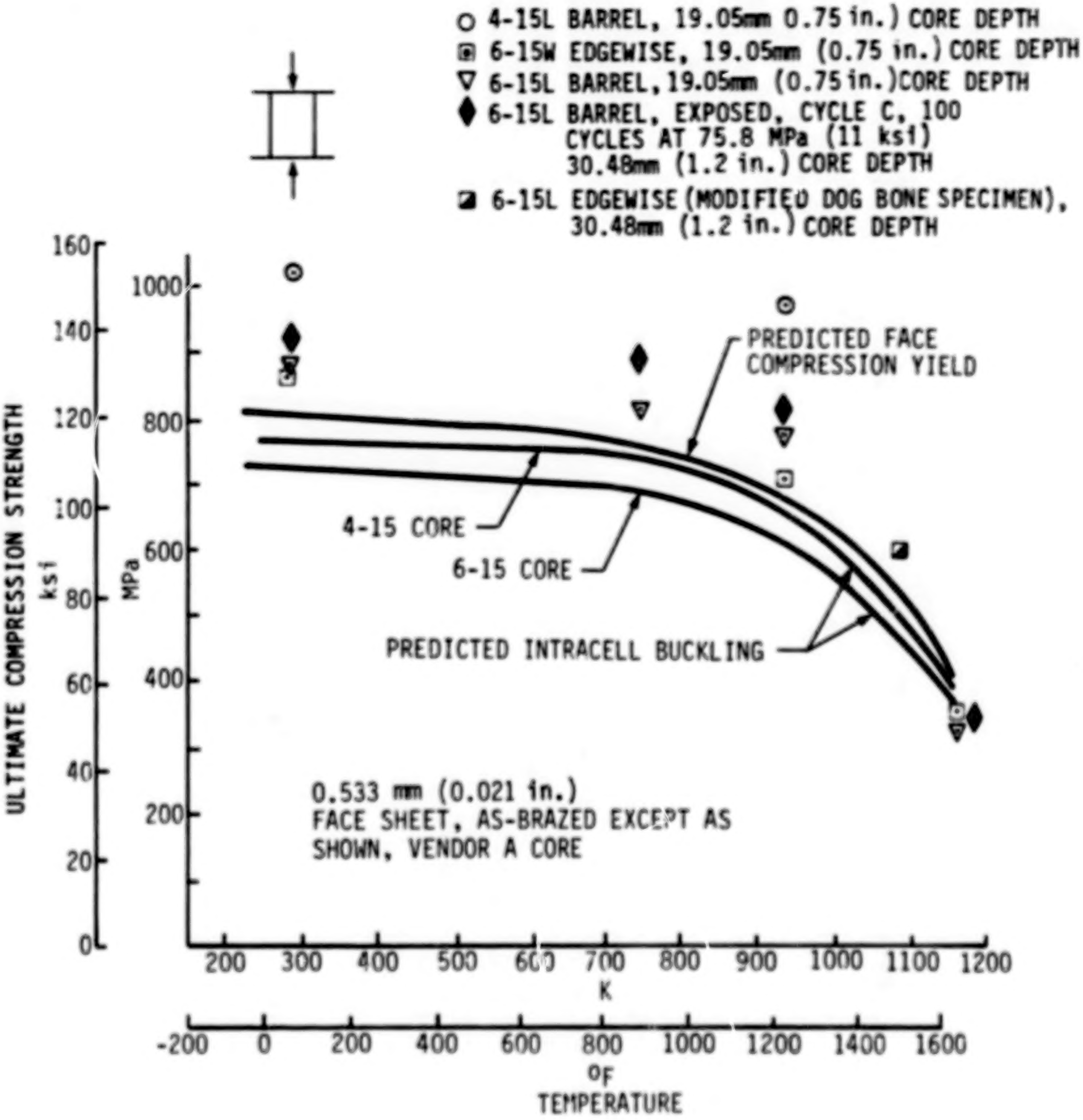


Figure 33
Edgewise Compression Strength vs Temperature.

Figure 34: Premature Shear Crimp Failure Due to Reaction of Potting Compound with Core Foil.

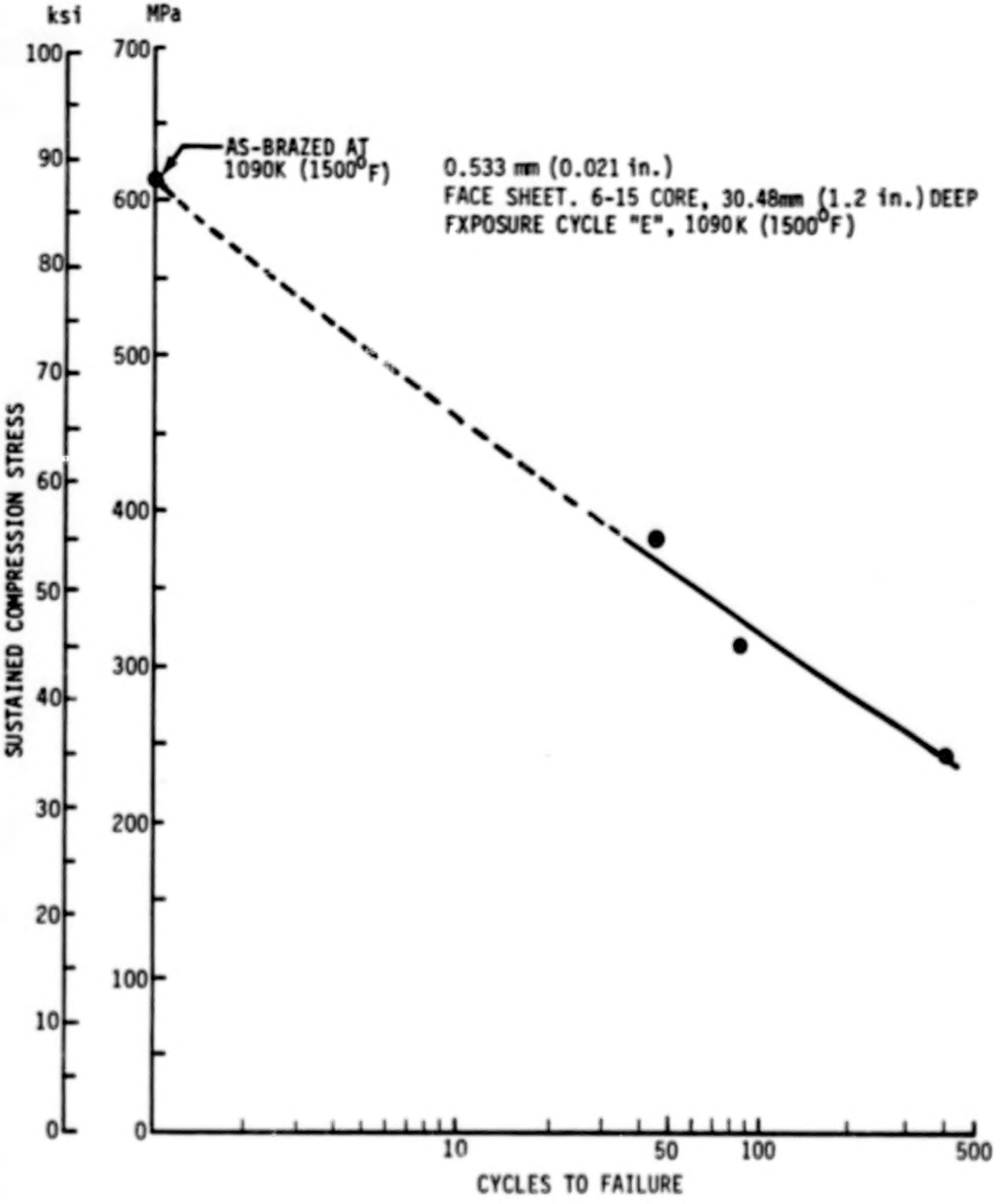
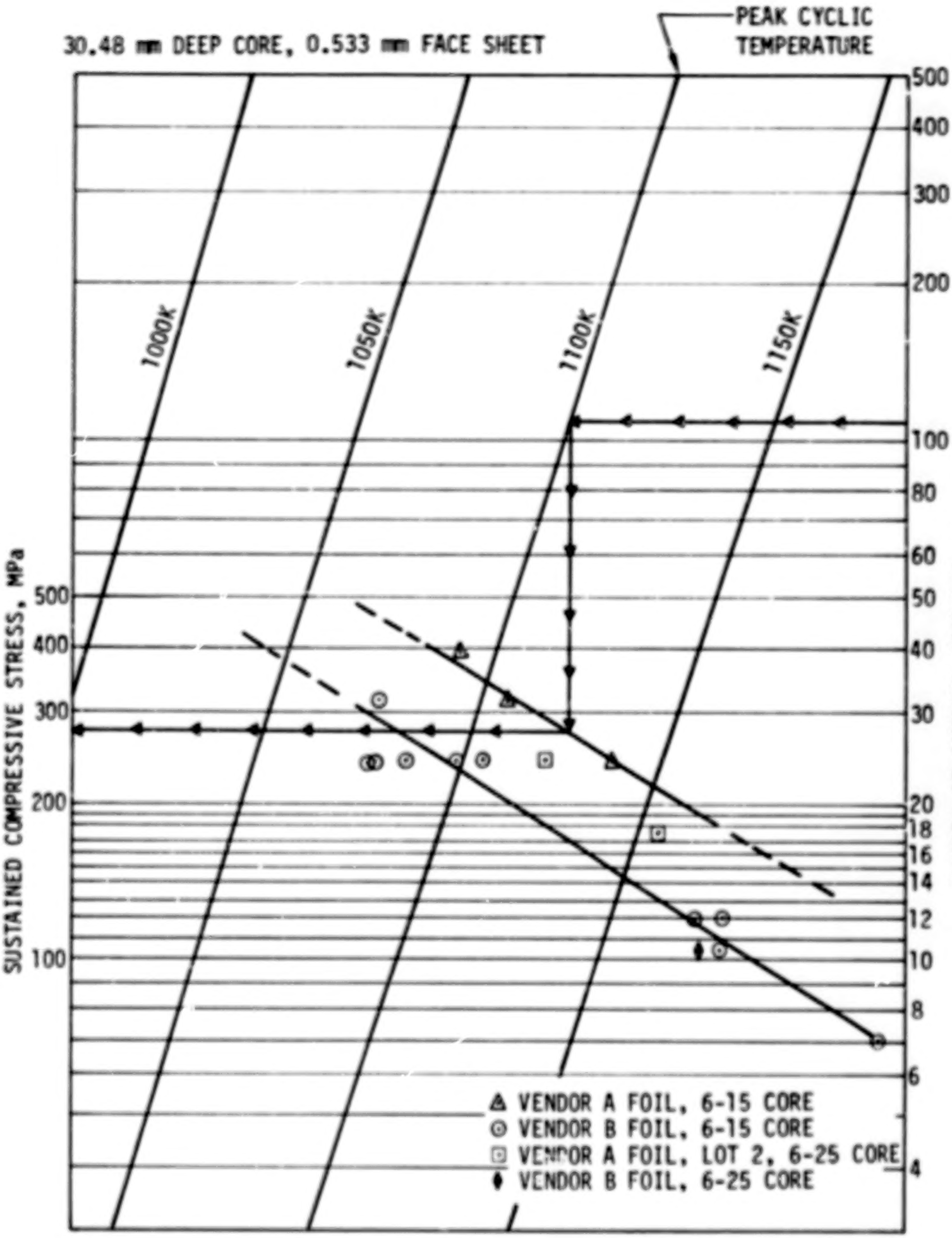


Figure 35
Edgewise Compression Life Prediction, Vendor A Core.



30.48 mm DEEP CORE, 0.533 mm FACE SHEET

Figure 36A: Prediction of Edgewise Compression Failure During Cyclic Thermal Exposure (SI Units).

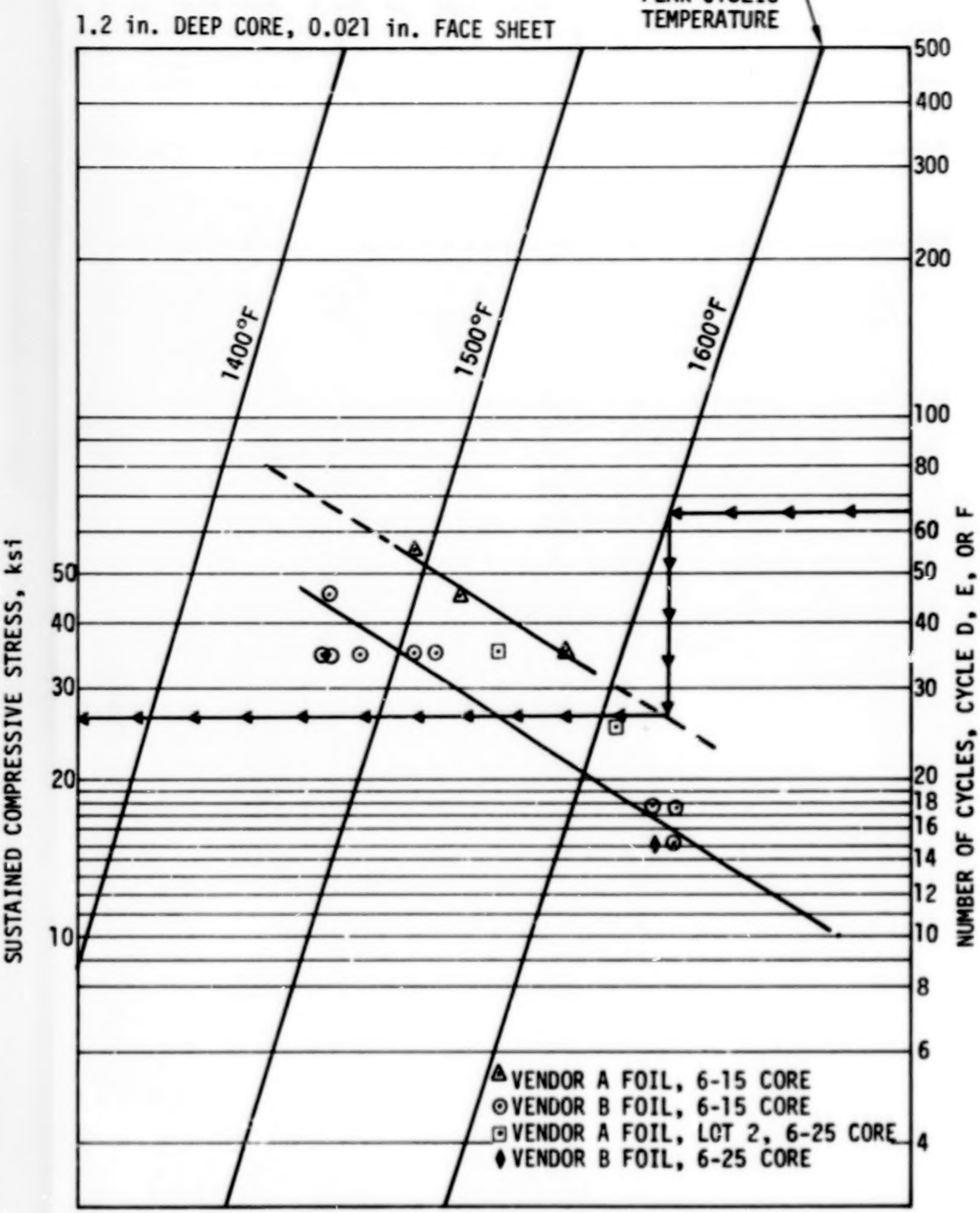
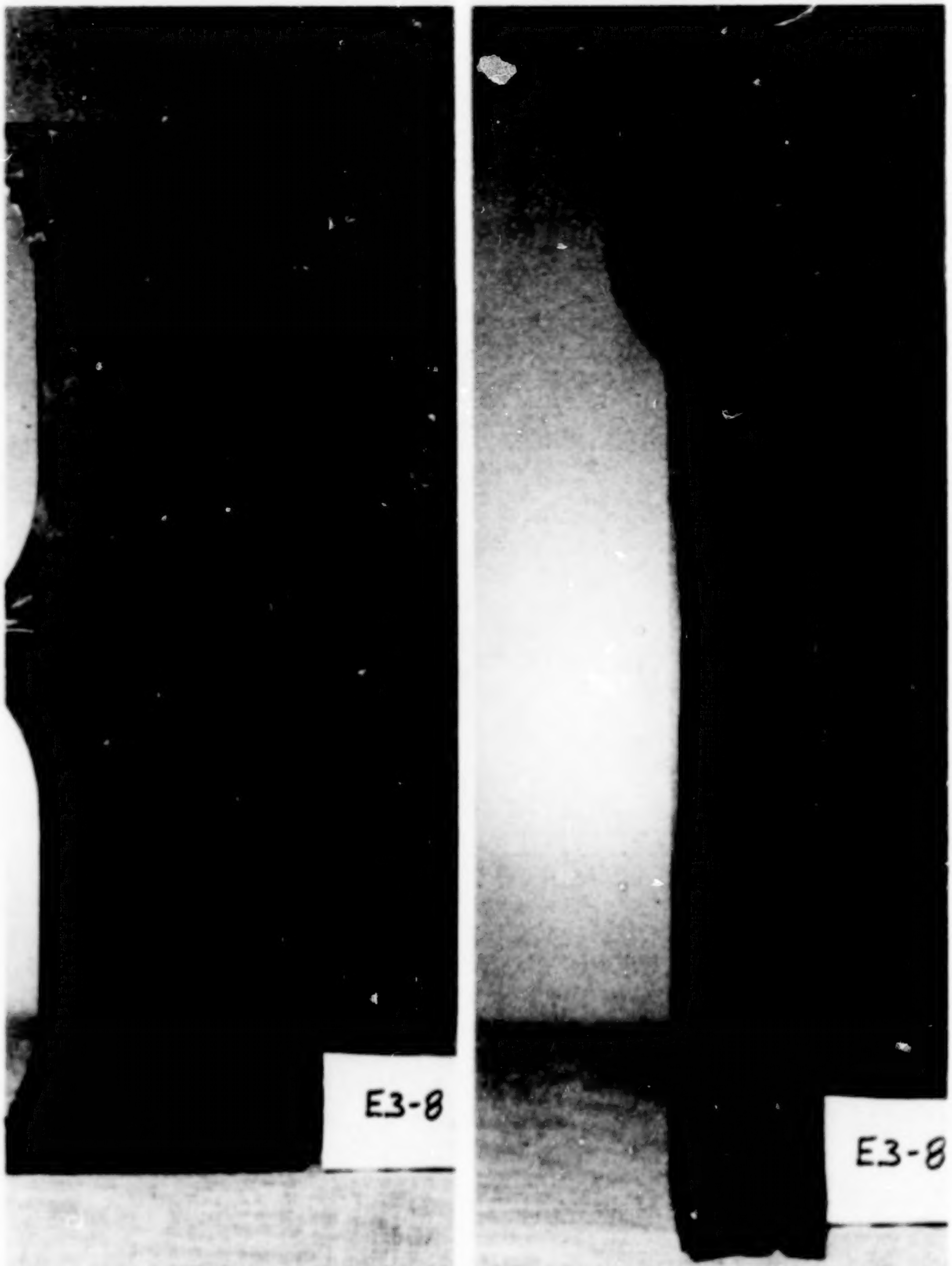
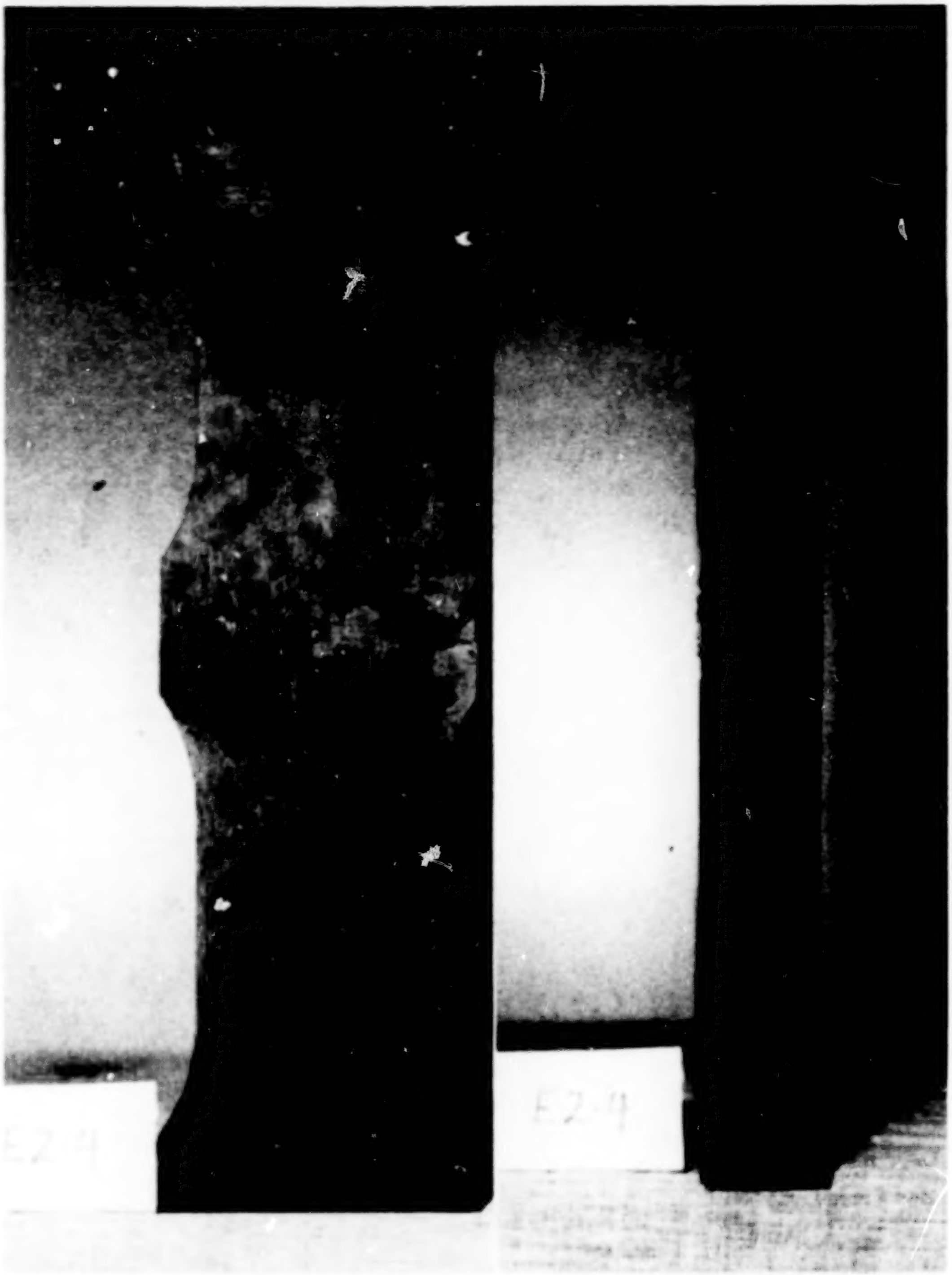


Figure 36b: Prediction of Edgwise Compression Failure During Cyclic Thermal Exposure (U.S. Units).



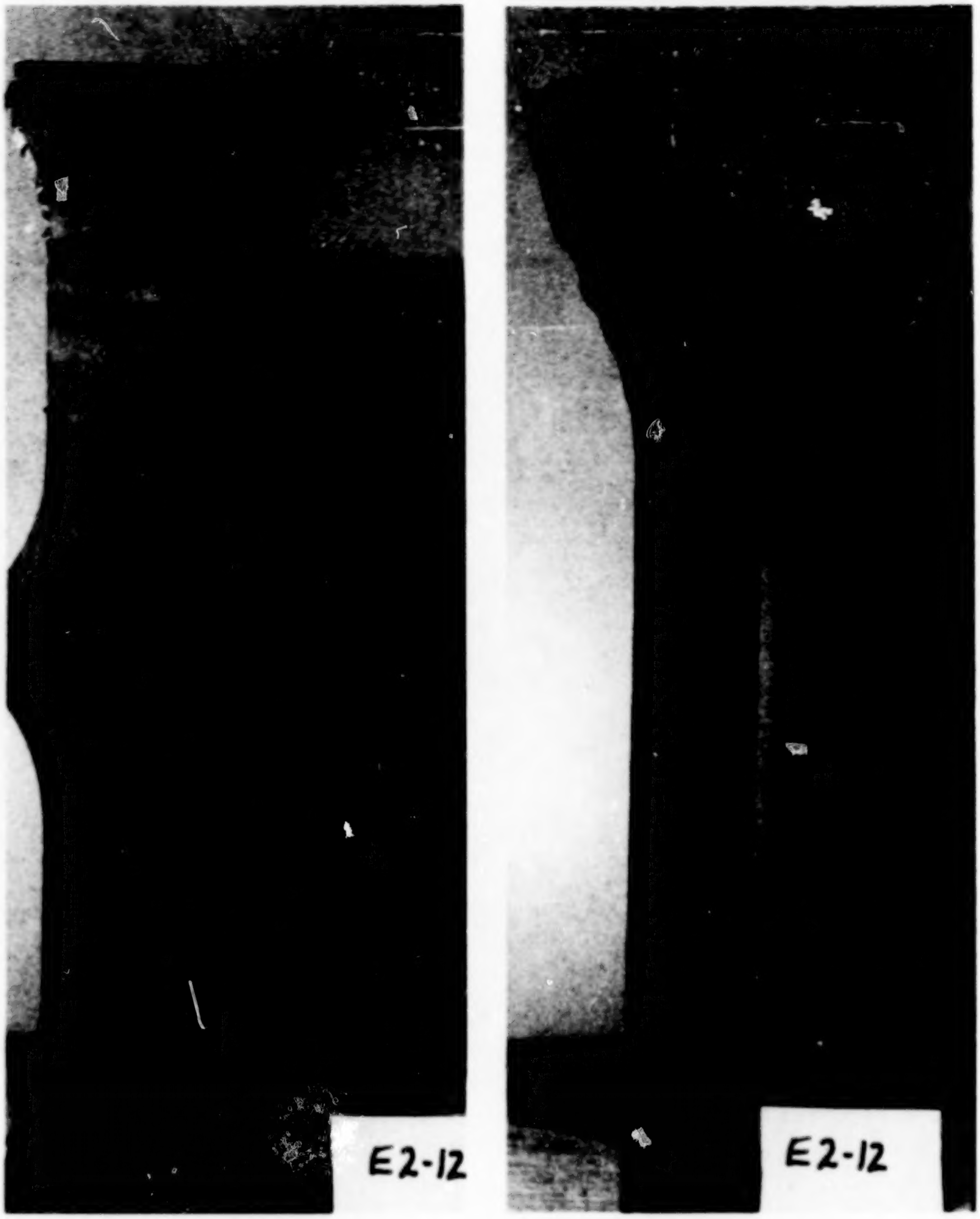
SPECIMEN NOS. E3-8 A & B. EXPOSED TO 1033K AT 241.3 MPa (1400°F AT 35 ksi), CYCLE D. FAILURE AT 99 CYCLES

Figure 37: Edgewise Compression Failure During Thermal Exposure.



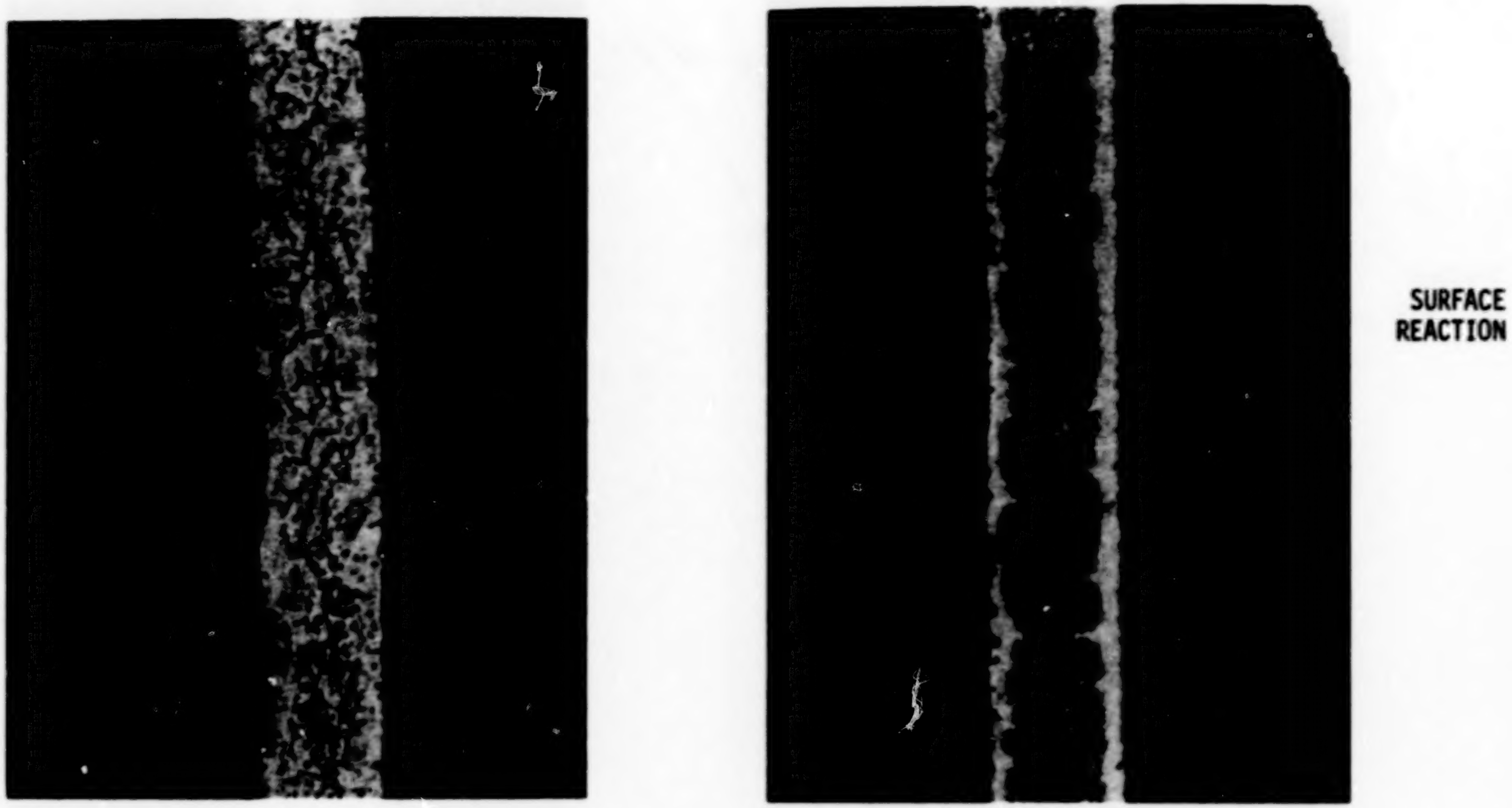
SPECIMEN NOS. E2-4 A AND B EXPOSED TO 1090K AT 241.3 MPa (1500°F AT 35 ksi), CYCLE FAILURE AT 6 CYCLES

Figure 38: Edgewise Compression Failure During Thermal Exposure.



SPECIMEN NOS. E2-12 A AND B EXPOSED TO 1144K AT 68.9 MPa (1500°F AT 10 ksi), CYCLE F. FAILURE AT 176 CYCLES

Figure 39: Edgewise Compression Failure During Thermal Exposure.


SURFACE REACTION

500X

VENDOR A FOIL, 283 CYCLES TO 1090K (1500°F) CYCLE E

500X

VENDOR B FOIL, 100 HOURS AT 1090K (1500°F)

Figure 40: Comparison of Vendor A and Vendor B Core Foils.

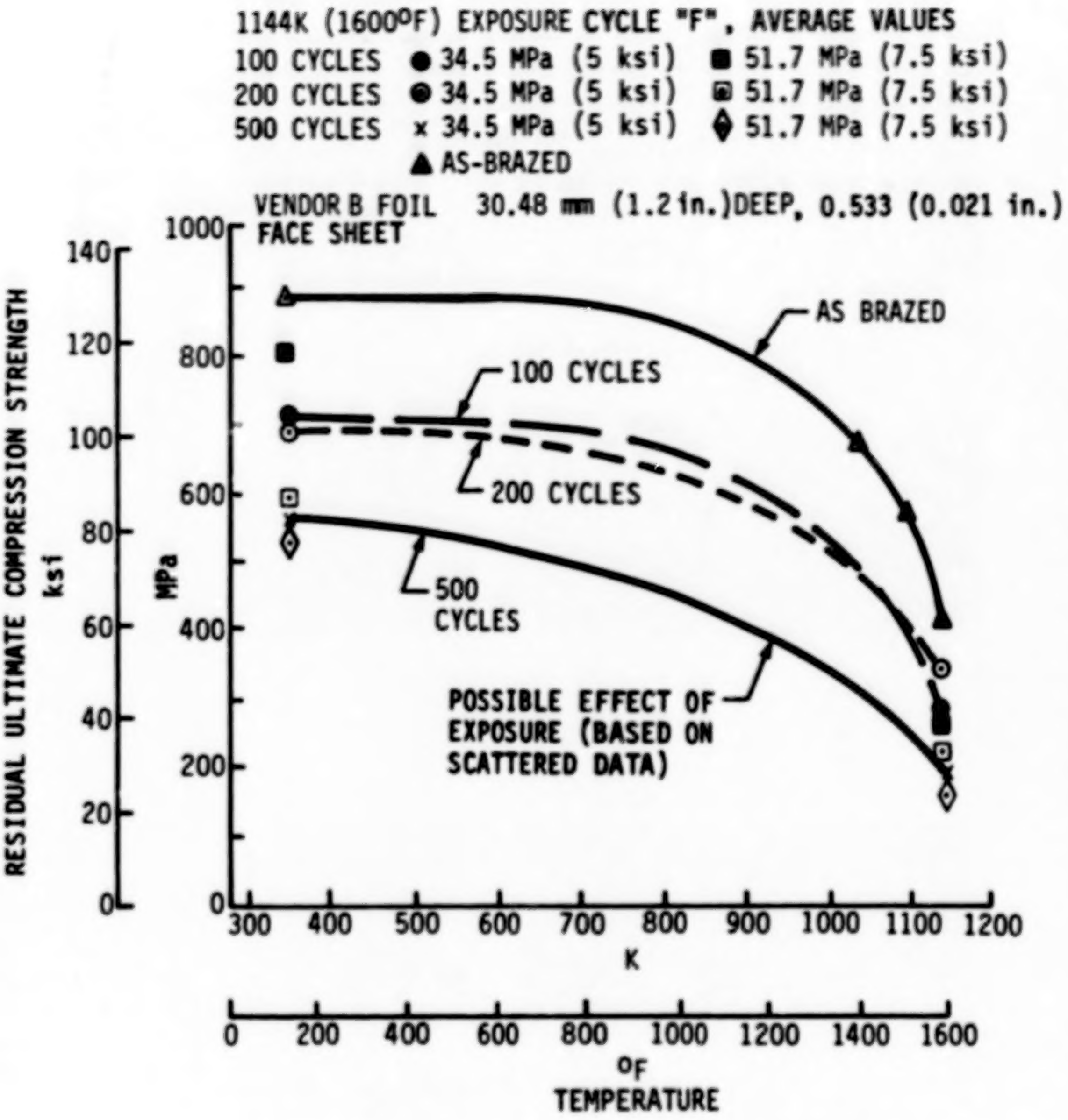


Figure 41
Edgewise Compression Strength vs Temperature.

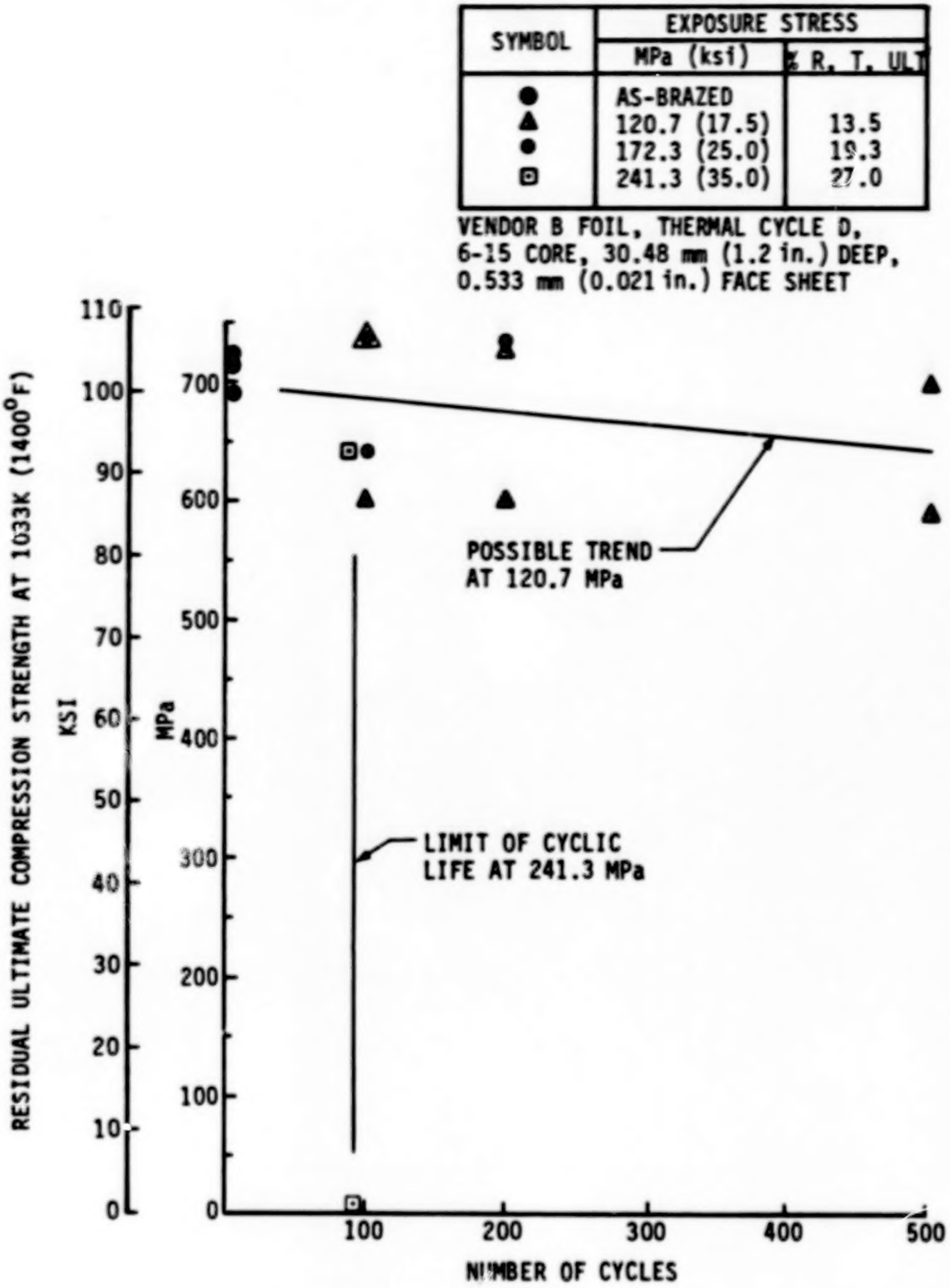
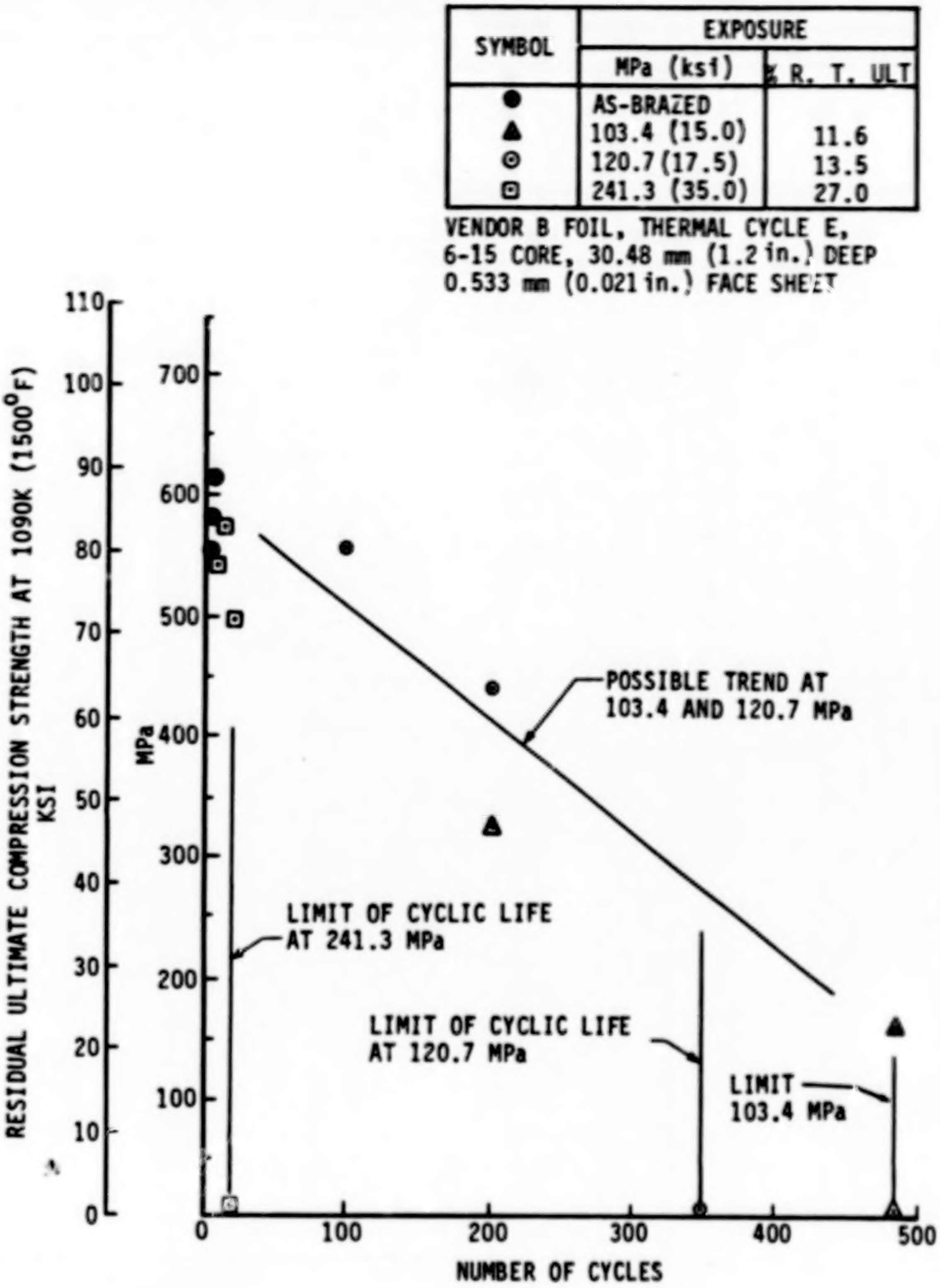


Figure 42: Effect of 1033K (1400°F) Cyclic Exposure on Edgewise Compression Strength at 1033K (1400°F).



SYMBOL	EXPOSURE	
	MPa (ksi)	% R. T. ULT
●	AS-BRAZED	
▲	103.4 (15.0)	11.6
⊙	120.7 (17.5)	13.5
⊡	241.3 (35.0)	27.0

VENDOR B FOIL, THERMAL CYCLE E,
6-15 CORE, 30.48 mm (1.2 in.) DEEP
0.533 mm (0.021 in.) FACE SHEET

Figure 43: Effect of 1090K (1500°F) Cyclic Exposure on Edgewise Compression Strength at 1090K (1500°F).

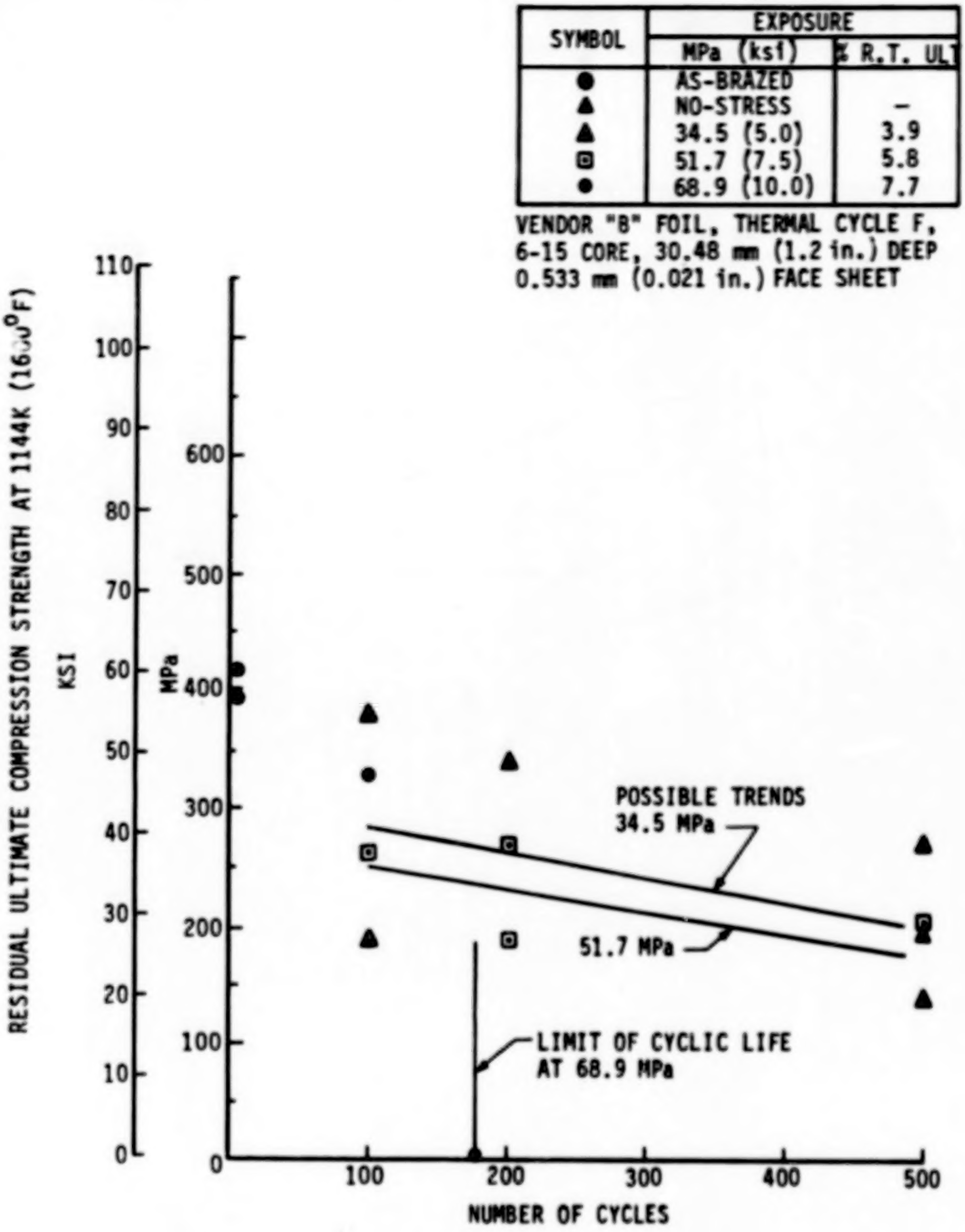


Figure 44: Effect of 1144K (1600°F) Cyclic Exposure on Edgewise Compression Strength at 1144K (1600°F).

EXPOSURE, 103.4 MPa (15 KSI)
AT 1090K (1500°F)(THERMAL CYCLE "E").
VENDOR "B" FOIL, 6-15 CORE 30.48 mm
(1.2 in.) DEEP, 0.533 mm (0.021 in.) FACE SHEET

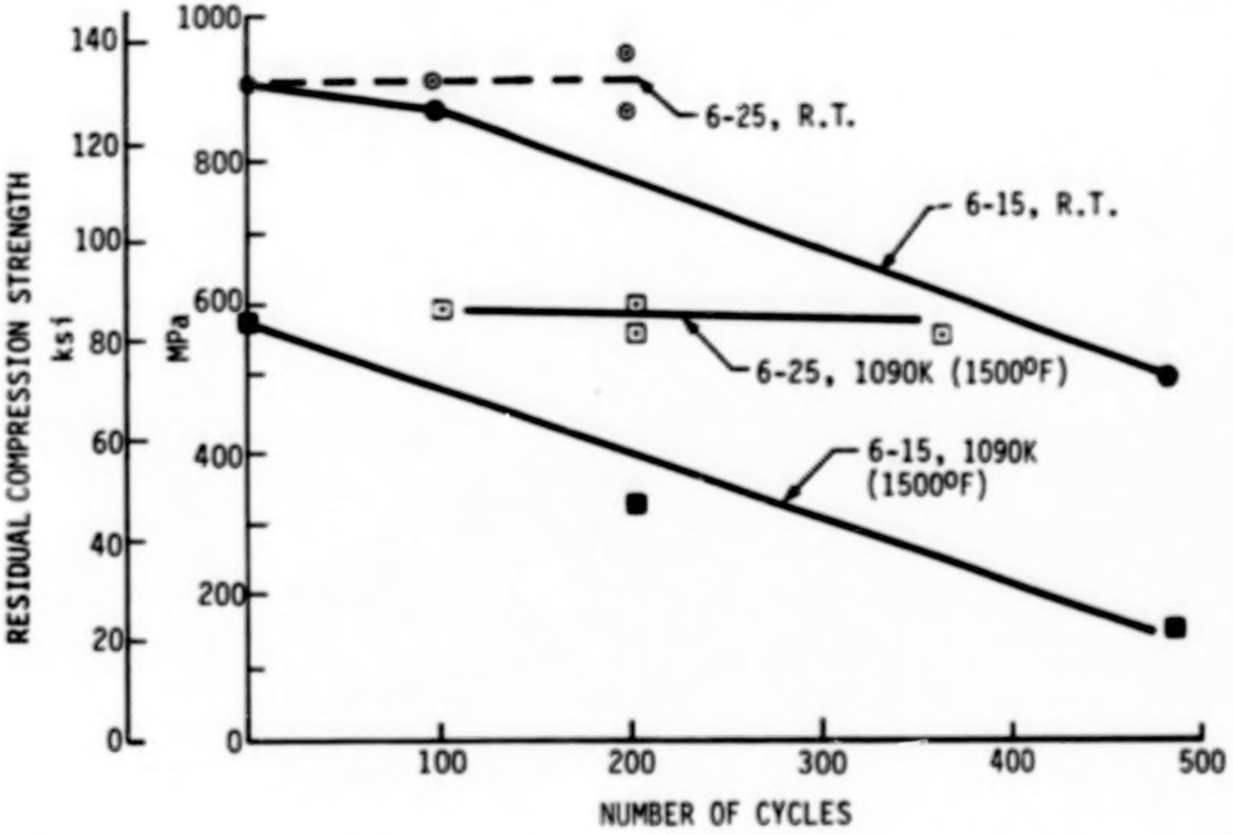


Figure 45
Effect of Core Foil Thickness on
Residual Compression Strength.

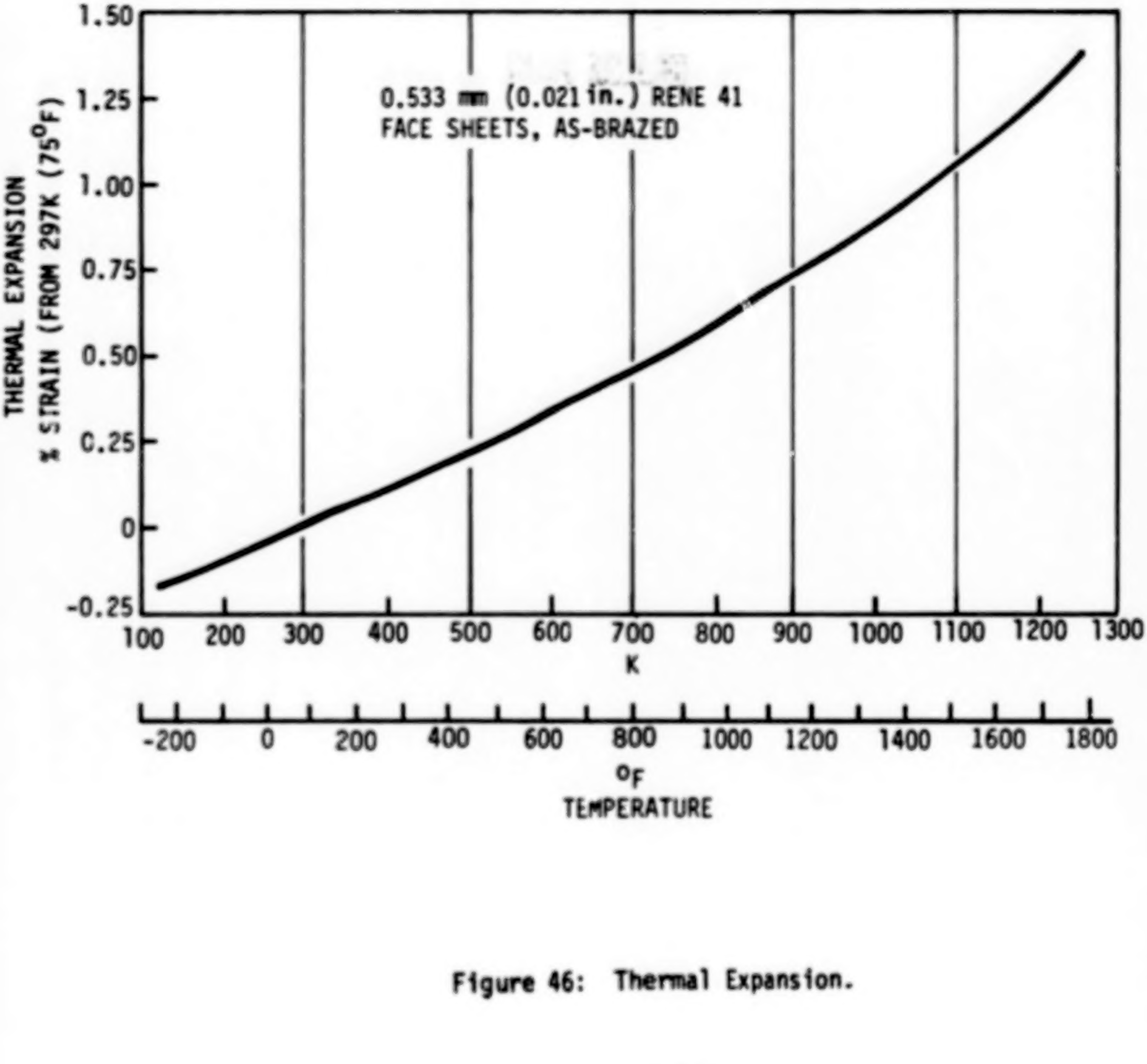


Figure 46: Thermal Expansion.

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TEST DATA TABULATION

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Base Metal - Test Type 1 (as received)

SPECIMEN NUMBER	NOMINAL THICKNESS (mm)	TEST TEMP (K)	TENSILE ULTIMATE (GPa)	TENSILE YIELD (GPa)	ELONGATION %
T1-1	0.279	297	0.939	0.461	44.
T1-2	0.279	297	0.954	0.448	45.
T1-3	0.279	297	0.964	0.461	45.
T1-4	0.279	922	0.743	0.410	28.
T1-5	0.279	922	0.753	0.404	29.
T1-6	0.279	922	0.745	0.408	27.
T2-1	0.533	297	1.000	0.638	42.
T2-2	0.533	297	1.004	0.635	42.
T3-3	0.533	297	0.973	0.527	48.
T3-4	0.533	297	0.973	0.517	47.
T2-5	0.533	922	0.834	0.547	29.
T2-6	0.533	922	0.819	0.547	28.
T2-7	0.533	922	0.798	0.499	31.
T2-8	0.533	922	0.811	0.490	33.

Base Metal Rene 41 Test Type 2

Heat Treat; 1311K (1900°F) 5 Minutes + 1200K (1700°F), 1 Hour

SPECIMEN NUMBER	NOMINAL THICKNESS mm	TEST TEMP K	TENSILE ULTIMATE GPa	TENSILE YIELD GPa	ELONGATION %
T1W-1	0.279	297	1.190	0.734	24
T1L-1	0.279	297	1.187	0.743	25
T1L-2	0.279	297	1.185	0.755	23
T1W-2	0.279	922	1.130	0.631	21
T1W-3	0.279	922	1.118	0.630	23
T1L-3	0.279	922	1.040	0.619	-
T2W-1	0.533	297	1.293	0.867	19.6
T2W-2	0.533	297	1.253	0.855	-
T2L-1	0.533	297	1.267	0.834	17.6
T2W-3	0.533	922	1.224	0.704	21
T2L-2	0.533	922	1.231	0.708	21
T2L-3	0.533	922	1.234	0.711	19

Brazed 0.279 mm (.011") Rene '41
TENSILE TESTS, Test Type 3, 4, and 5

TEST TYPE	SPECIMEN NUMBER	TEST TEMP K	TENSILE ULTIMATE GPa	TENSILE YIELD GPa	ELONGATION %
5	TB7LB-1	297	1.008	0.899	[1]
4	TB7LT-1	297	1.009	0.840	3.2
4	TB7LT-7	297	1.003	0.840	3.2
[illegible]	TB8LB-1	297	1.047	0.903	2.4
4	TB8LB-7	297	1.027	0.875	3.0
4	TB8LB-11	297	1.013	0.878	2.4
4	TB8LB-12	297	0.996	0.863	2.5
4	TB8LT-1	297	1.046	0.876	3.4
4	TB8LT-7	297	0.975	0.846	2.4
5	TB9LB-1	297	1.027	0.920	1.8
4	TB9LB-7	297	1.034	0.871	3.2
4	TB9LB-10	297	0.986	0.864	2.1
5	TB9LT-1	297	0.946	0.837	1.5
4	TB10LB-1	297	1.079	0.859	5.0
4	TB10LT-1	297	1.056	0.830	5.1
4	TB10WB-1	297	1.035	0.854	4.0
4	TB10WB-2	297	1.080	0.854	5.0
5	TB10WB-3	297	.967	0.849	1.8
3	TB10WB-4	297	1.200	0.820	10.0
4	TB10WT-1	297	1.035	0.872	3.1
4	TB10WT-2	297	1.035	0.856	3.6
5	TB10WT-3	297	.980	0.878	1.6
4	TB10WB-6	297	1.092	0.848	5.0
5	TB10WB-7	297	1.048	0.864	3.0
3	TB10WB-8	297	1.149	0.793	9.0
4	TB7LB-3	218	1.079	0.930	2.6
4	TB8LB-3	218	1.087	0.949	2.4
4	TB9LB-3	218	1.079	0.952	2.4
4	TB7LB-4	755	0.898	0.807	1.8
4	TB8LB-4	755	0.854	0.797	1.1
4	TB9LB-4	755	0.929	0.810	2.4
4	TB7LB-5	922	0.989	0.729	3.8
4	TB8LB-5	922	0.965	0.747	3.2
4	TB9LB-5	922	0.969	0.723	3.6
5	TB7LB-6	1144	0.515	–	[1]
5	TB8LB-6	1144	0.532	0.377	11.0
5	TB9LB-6	1144	0.523	0.374	10.0

[1] failed outside gage section

Brazed Rene '41 SHEET

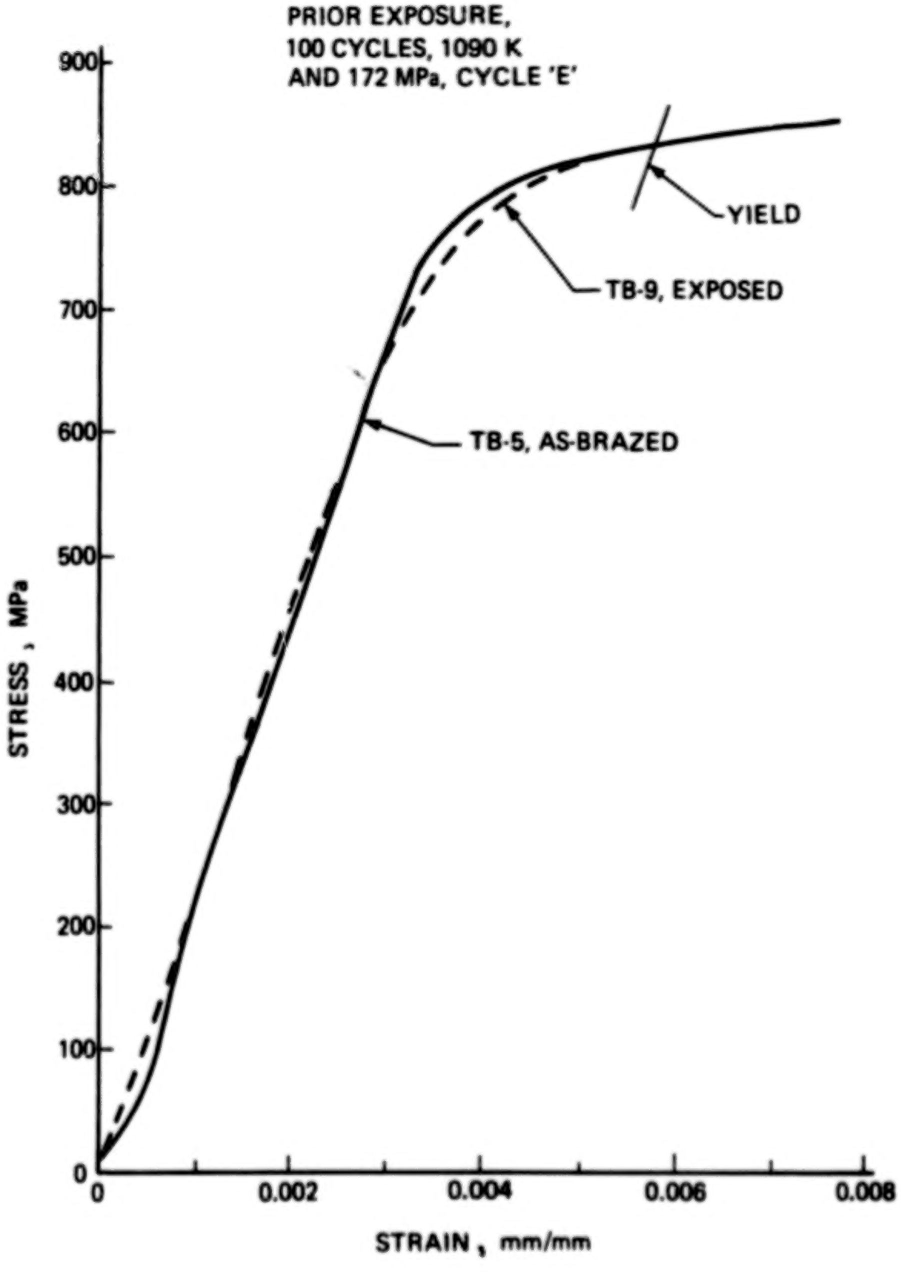
Tensile Tests, Test type 4 and 5

TEST TYPE	SPEC NUMBER	NOMINAL THICK (mm) [1]	TEST TEMP K	TENSILE ULTIMATE GPa	TENSILE YIELD GPa	ELONGATION % [2]	TENSILE MODULUS GPa
5	TB4LT-1	0.533	297	1.107	0.871	5.0	[3]
5	TB4LT-2	0.533	297	1.142	0.870	6.0	[3]
5	TB5LT-1	0.533	297	1.054	0.805	5.0	[3]
5	TB5LT-2	0.533	297	1.082	0.817	6.0	[3]
5	TB6LT-1	0.533	297	1.027	0.811	5.0	[3]
4	TB6LT-3	0.533	297	1.077	0.769	8.3	[3]
4	TB6WB-1	0.533	297	1.218	0.880	10.6	[3]
4	TB6WT-1	0.533	297	1.114	0.763	10.4	[3]
5	TB4LT-3	0.533	922	0.949	0.765		[3]
4	TB5LT-3	0.533	922	1.139	0.705	8.0	[3]
4	TB6LT-2	0.533	922	1.067	0.648	10.0	[3]
5	TB-8	0.533	82	1.129	1.019	2.1	262.1×10^3
5	TT-8	0.533	83	1.143	1.006	2.8	258.0
5	TB-9	0.533	297	1.033	0.813	5.9	221.0
5	TT-9	0.533	297	1.088	0.820	7.9	249.9
5	TB-10	0.533	811	0.861	0.709	8.5	205.2
5	TT-10	0.533	811	0.944	0.730	6.7	201.7
5	TB-11	0.533	1033	0.902	0.668	12.6	174.2
5	TT-11	0.533	1033	0.882	0.665	13.8	171.5
5	TB-12	0.533	1144	0.496	0.362	19.1	117.3
5	TT-12	0.533	1144	0.499	0.351	15.0	153.2

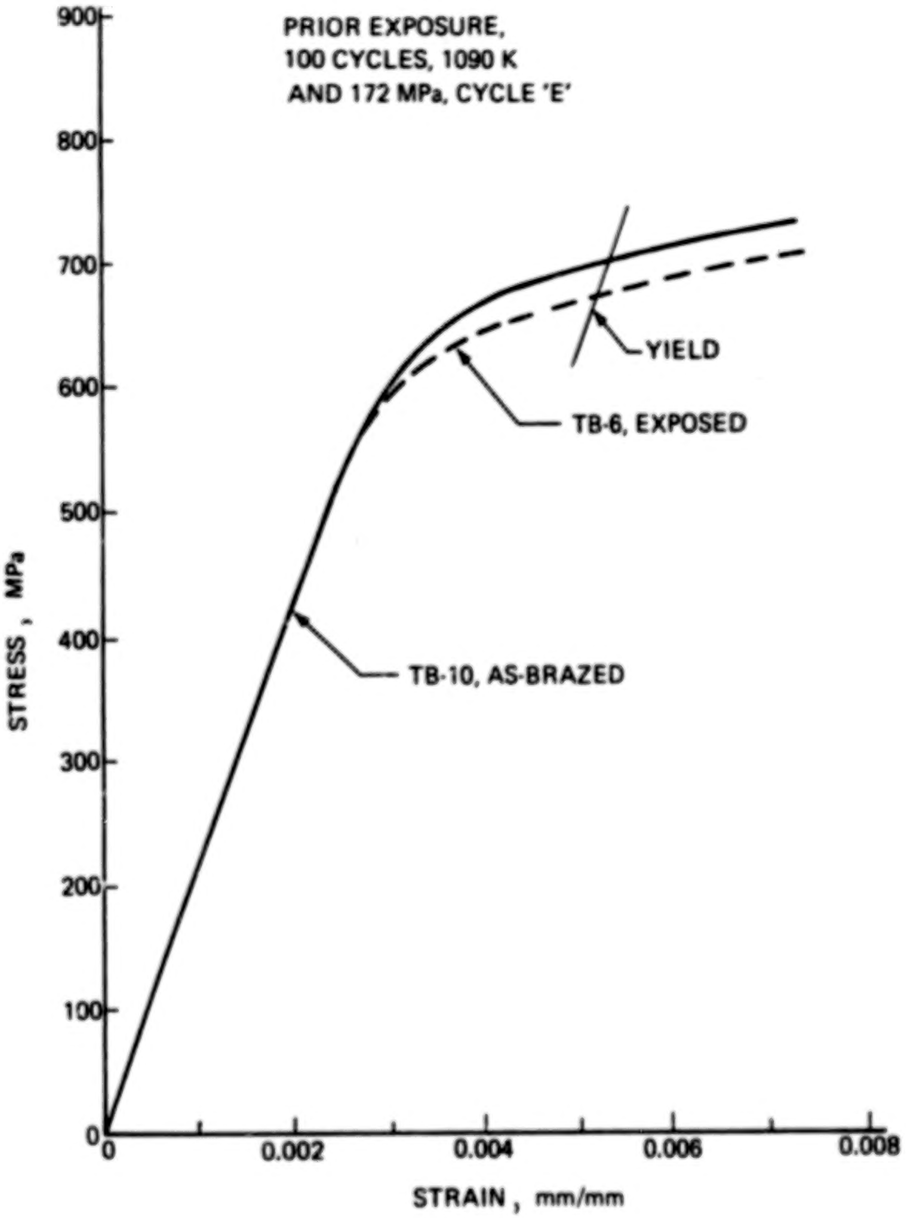
[1] Stress values based on average thickness of each material lot

[2] measured in 50.8 mm (2 in.) gage length

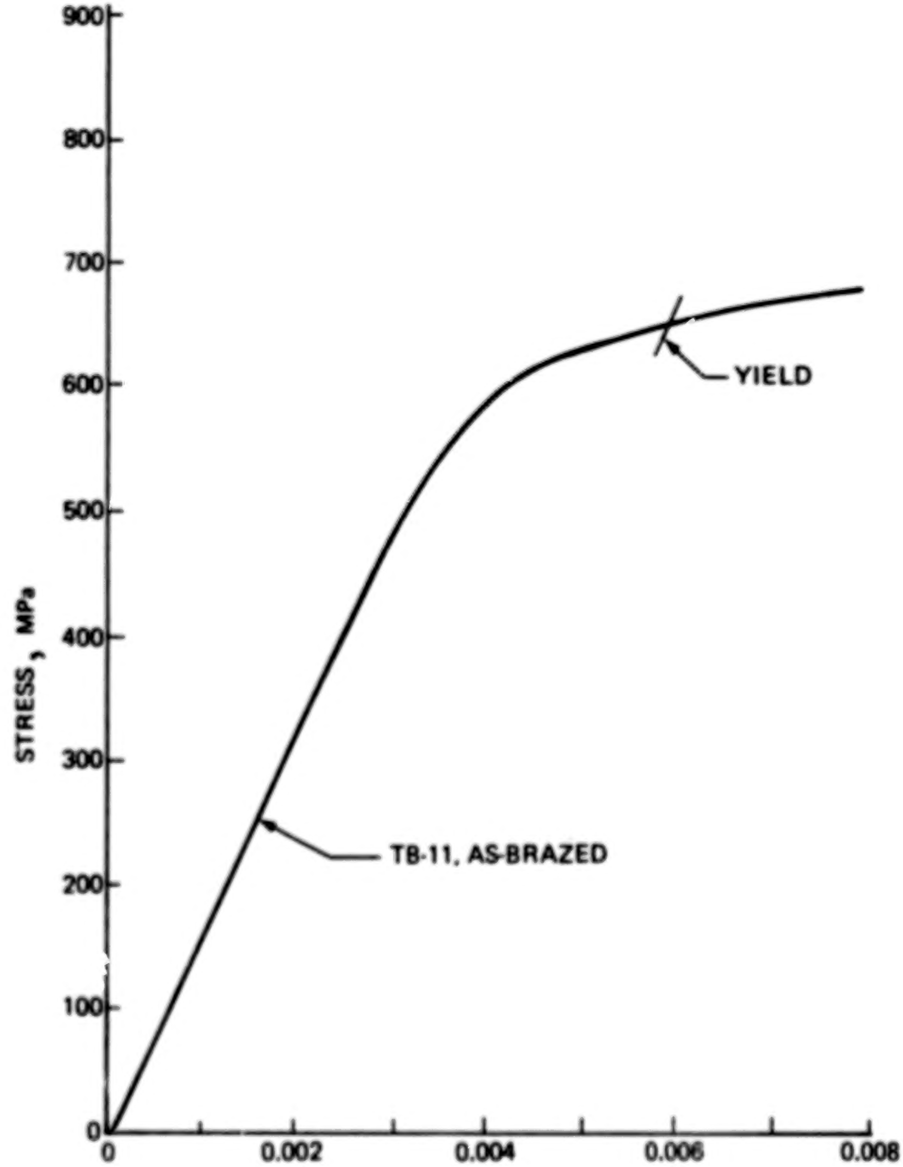
[3] not determined



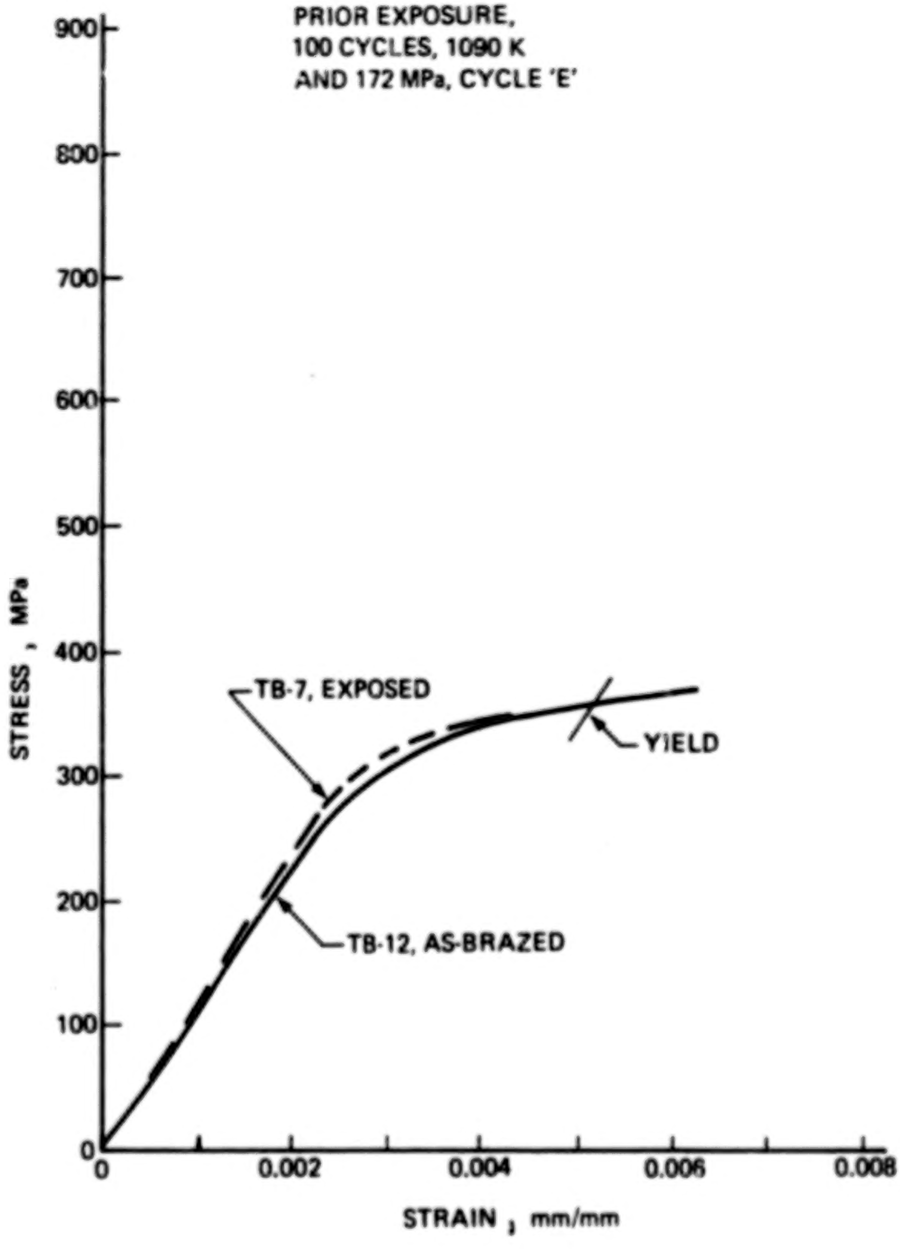
TENSILE STRESS/STRAIN CURVES AT 297 K



TENSILE STRESS/STRAIN CURVES AT 811 K



TENSILE STRESS/STRAIN CURVES AT 1033 K



TYPICAL TENSILE STRESS/STRAIN CURVES AT 1144 K

Brazed 0.279 Rene' 41 Sheet Residual Strength After Thermal Exposure

Tensile Tests - Test Type 14

SPECIMEN NUMBER	CYCLIC CONDITIONS				TEST TEMP	TENSILE ULTIMATE GPa	TENSILE YIELD GPa	ELONGATION %
	STRESS GPa	MAX. TEMP. K	# CYCLES	TIME PER CYCLE SEC.				
TB7LT-2C	0.184	1144	100	45	297	0.994	0.824	3.0
TB8LT-2C	0.184	1144	100	45	297	1.016	0.849	2.8
TB9LT-2C	0.184	1144	100	45	297	0.905	0.823	7.8
TB7LT-3D	0.221	1144	100	45	297	0.989	0.878	1.6
TB8LT-3D	0.221	1144	100	45	297	1.038	0.907	2.4
TB9LT-3D	0.221	1144	100	45	297	0.971	0.869	13.2
TB7LT-4E	0.221	1144	300	45	297	0.964	0.919	.75
TB8LT-4E	0.221	1144	300	45	297	0.998	0.907	6.5
TB9LT-4E	0.221	1144	300	45	297	0.927	0.869	3.2
TB7LT-5F	0.221	1144	500	45	297	0.824	0.907	.35
TB8LT-5F	0.221	1144	500	45	297	0.957	0.920	2.5
TB7LT-6G	0.259	1144	100	45	297	1.007	0.940	1.2
TB8LT-6G	0.259	1144	100	45	297	0.989	0.940	.8
TB9LT-6G	0.259	1144	100	45	297	0.957	0.920	4.0
TB7LB-2D	0.221	1144	100	45	755	0.920	0.824	2.2
TB8LB-2D	0.221	1144	100	45	755	0.969	0.829	3.2
TB9LB-2D	0.221	1144	100	45	755	0.981	0.830	3.2
TB7LT-3C	0.184	1144	100	45	922	1.037	0.716	5.2
TB8LT-8C	0.184	1144	100	45	922	1,021	0.699	5.0
TB9LT-8C	0.184	1144	100	45	922	0.883	0.710	2.4
TB7LT-9D	0.221	1144	100	45	922	0.926	0.748	2.6
TB8LT-9D	0.221	1144	100	45	922	0.927	0.753	2.4
TB9LT-9D	0.221	1144	100	45	922	0.904	0.759	2.2
TB7LT-10E	0.221	1144	300	45	922	0.852	0.765	1.0
TB8LT-10E	0.221	1144	300	45	922	0.926	0.754	2.2
TB9LT-10E	0.221	1144	300	45	922	0.835	0.729	1.6
TB7LT-11F	0.221	1144	500	45	922	0.870	0.772	1.2
TB8LT-11F	0.221	1144	500	45	922	0.896	0.756	1.6
TB9LT-11F	0.221	1144	500	45	922	0.856	0.756	1.4
TB7LT-12G	0.259	1144	100	45	922	0.975	0.293	2.6
TB8LT-12G	0.259	1144	100	45	922	0.894	0.802	1.4
TB9LT-12G	0.259	1144	100	45	922	0.909	0.781	1.8
TB7LB-8D	0.221	1144	100	45	1144	0.529	0.371	16.5
TB8LB-8D	0.221	1144	100	45	1144	0.512	0.363	18.5
TB9LB-8D	0.221	1144	100	45	1144	0.499	0.360	19.2

Brazed 0.533 Rene' 41 Sheet   Tensile Tests - Braze Fillets on Test Type 15

Cyclic Condition: 100 Cycles at 1090K and 0.172 GPa (Cycle E)

SPECIMEN NUMBER	TEST TEMP K	TENSILE ULTIMATE GPa	TENSILE YIELD GPa	ELONGATION %	TENSILE MODULUS GPA
TB-4	78	1.171	1.019	2.1	248.6×10^3
TT-4	78	1.191	1.047	2.9	241.3
TB-5	297	0.978	0.826	3.1	221.0
TT-5	297	1.026	0.826	4.3	229.6
TB-6	811	0.957	0.685	6.9	219.2
TT-6	811	0.916	0.709	4.4	201.3
TB-7	1144	0.503	0.358	14.3	135.1
TT-7	1144	0.499	0.351	14.3	162.7

Face Sheet - Subjected to Braze Thermal Cycle Compression Tests - Test Type 7

SPECIMEN NUMBER	SHEET THICKNESS mm	TEST TEMP. K	COMPRESSION YIELD GPa
CB4T-1	0.544	279	0.923
CB5T-1	0.544	279	0.840
CB6T-1	0.533	279	0.792
CB4T-2	0.544	1144	0.796
CB5T-2	0.544	1144	0.743
CB6T-2	0.533	1144	0.661

Base Metal - As Received

Compression Tests - Test Type 6

SPECIMEN NUMBER	SHEET THICKNESS mm	TEST TEMP. K	COMPRESSION YIELD GPa
C2-1	0.533	279	0.427
C2-2	0.546	279	0.434
C2-4	0.538	279	0.298
C2-5	0.546	1144	0.610
C2-7	0.546	1144	0.572
C2-8	0.538	1144	0.560

Brazed Rene 41 Honeycomb Sandwich

Peel Strength Tests

Vendor A Foil - Exposed - Test Type 16

6-15 Core Type, 0.533 mm Face Sheet, 19.05 mm Core Depth

SPECIMEN NUMBER	STRESS	CYCLIC CONDITIONS			TEST TEMP. K	PEEL STRENGTH J/mm
		MAX. TEMP K	# CYCLES	TIME PER CYCLE min.		
P11LT-2N	0	1033	500	13.5	297	0.662
P12LT-2N	0	1033	500	13.5	297	0.721
P13LT-2N	0	1033	500	13.5	297	0.422
P14LB-2N	0	1033	500	13.5	297	0.785
P15LT-2N	0	1144	500	13.5	297	0.593

Vendor A Foil - As Brazed - Test Type 13

0.533 mm face sheet, 19.05 mm core depth

SPECIMEN NUMBER	CORE TYPE	TEST TEMP. K	PEEL STRENGTH J/mm
P4LT-1	4-15(L)	297	0.951
P4LB-2	4-15(L)	297	0.892
P5LT-1	4-15(L)	297	1.068
P5LB-2	4-15(L)	297	0.545
P6LT-1	4-15(L)	297	1.244
P11LT-1	6-15(L)	297	0.700
P12LT-1	6-15(L)	297	0.721
P13LT-1	6-15(L)	297	0.651
P14LB-1	6-15(L)	297	1.047
P15LT-1	6-15(L)	297	0.465

Brazed Rene'41 Honeycomb Sandwich

Flatwise Tension Tests

Vendor A Foil - Residual Strength - Test Type 17

6-15 Core, 0.533 Face Sheet, 19.05 mm Core Depth

SPECIMEN NUMBER	EXPOSURE CONDITION							TEST TEMP. K	ULTIMATE LOAD KN	ULTIMATE STRENGTH GPa
	CYCLIC				EXPOSURE					
	STRESS MPa	MAX. TEMP. K	# CYCLES	CYCLE TIME MIN.	STRESS MPa	TEMP. K	TIME hrs.			
F11-7J	0	1144	100	2.7	0.591	1033	7.5	297	15.9	0.62
F14-7J	0	1144	100	2.7	0.591	1033	7.5	297	15.3	0.59
F15-8J	0	1144	100	2.7	0.591	1033	7.5	297	15.5	0.60
F11-11J	0	1144	100	2.7	0	1033	7.5	297	15.5	0.60
F14-11J	0	1144	100	2.7	0	1033	7.5	297	17.8	0.69
F15-11J	0	1144	100	2.7	0	1033	7.5	297	17.0	0.66
F11-8J	0	1144	100	2.7	0.591	1033	7.5	922	13.9	0.54
F14-8J	0	1144	100	2.7	0.591	1033	7.5	922	12.1	0.47
F15-7J	0	1144	100	2.7	0.591	1033	7.5	922	[1]	
F11-9J	0	1144	100	2.7	0.591	1033	7.5	1144	5.7	0.22
F14-9J	0	1144	100	2.7	0.591	1033	7.5	1144	6.41	0.25
F15-9J	0	1144	100	2.7	0.591	1033	7.5	1144	7.1	0.28
F11-10K	0	1144	500	2.7	0.591	1033	37.5	1144	6.6	0.26
F14-10K	0	1144	500	2.7	0.591	1033	37.5	1144	6.5	0.25
F15-10K	0	1144	500	2.7	0.591	1033	37.5	1144	6.4	0.25

[1] Specimen damaged, not tested

Brazed Rene 41'Honeycomb Sandwich

Flatwise Tension Tests

Vendor A Foil - As Brazed - Test Type 11

0.533 mm Face, 19.05 mm Core Depth

SPECIMEN NUMBER	CORE TYPE	▷1	TEST TEMP. K	ULTIMATE LOAD KN	ULTIMATE STRENGTH GPa
F4-1	4-15	B	297	29.0	1.12
R4-2	4-15	BR	297	29.4 ▷2	1.14
F5-1	4-15	B	297	28.8	1.12
F5-2	4-15	B	297	27.8 ▷2	1.08
F6-1	4-15	B	297	29.6	1.14
F11-1	6-15	B	297	17.7	0.68
F11-2	6-15	BR	297	17.1	0.66
F12-1	6-15	B	297	18.2	0.71
F12-2	6-15	B	297	17.6	0.68
F13-1	6-15	B	297	17.0	0.66
F13-2	6-15	B	297	16.5	0.64
F14-1	6-15	B	297	17.8	0.69
F14-2	6-15	BR	297	15.6	0.60
F15-1	6-15	B	297	17.7	0.68
F15-2	6-15	BR	297	17.8	0.69
F11-3	6-15	B	219	18.8	0.73
F14-3	6-15	B	219	19.4	0.74
F15-3	6-15	B	219	18.6	0.72
F11-4	6-15	BR	755	16.4	0.63
F14-4	6-15	BR	755	▷2	
F15-4	6-15	BR	755	▷2	
F4-3	4-15	BR	922	23.4	0.91
F5-3	4-15	BR	922	26.9	1.04
F6-3	4-15	BR	922	27.8	1.07
F11-5	6-15	BR	922	19.2	0.63
F14-5	6-15	BR	922	14.9	0.61
F15-5	6-15	BR	922	16.3	0.63
F4-4	4-15	BR	1144	13.2	0.49
F5-4	4-15	BR	1144	12.5	0.48
F6-4	4-15	BR	1144	12.2	0.47
F11-6	6-15	BR	1144	8.0	0.31
F14-6	6-15	BR	1144	7.3	0.28
F15-5	6-15	BR	1144	7.7	0.30

▷1 B = loading blocks bonded to specimen
BR = loading blocks brazed to specimen at 1261K

▷2 Bond or braze failure from loading block

Brazed Rene' 41 Honeycomb Sandwich

Core Compression Tests

Vendor A Foil - As Brazed - Test Type 12

0.533 mm Face Sheet, 19.05 mm Core Depth

SPECIMEN NUMBER	CORE TYPE	TEST TEMP K	ULTIMATE LOAD KN	ULTIMATE STRENGTH MPa
CC4-1	4-15	279	26.40	4.482
CC4-2	4-15	279	30.25	5.171
CC5-1	4-15	279	27.97	4.757
CC5-2	4-15	279	24.74	4.206
CC6-1	4-15	279	29.54	5.033
CC11-1	6-15	279	10.17	1.737
CC12-1	6-15	279	9.14	1.565
CC13-1	6-15	279	11.99	2.048
CC14-1	6-15	279	11.43	1.951
CC15-1	6-15	279	12.01	2.055
CC11-2	6-15	219	13.16	2.248
CC14-2	6-15	219	12.44	2.124
CC15-2	6-15	219	14.43	2.468
CC11-3	6-15	755	10.26	1.751
CC14-3	6-15	755	9.84	1.682
CC15-3	6-15	755	10.58	1.806
CC4-3	4-15	922	21.87	3.737
CC5-3	4-15	922	21.51	3.675
CC6-3	4-15	922	22.90	3.916
CC11-4	6-15	922	9.52	1.627
CC14-4	6-15	922	8.96	1.531
CC15-4	6-15	922	9.55	1.634
CC4-4	4-15	1144	14.48	2.475
CC5-4	4-15	1144	14.43	2.468
CC6-4	4-15	1144	14.99	2.565
CC11-5	6-15	1144	7.13	1.220
CC14-5	6-15	1144	7.04	1.200
CC15-5	6-15	1144	6.86	1.172

Brazed Rene' 41 Honeycomb Sandwich Core Shear Tests

Vendor B Foil - As Brazed - Test Type 8

SPECIMEN NUMBER	CORE TYPE [1]	CORE DEPTH mm	TEST TEMP K	ULTIMATE SHEAR STRENGTH MPa
C5-8-1	6-15(L)	30.48	297	0.950
C5-8-2	6-15(L)	30.48	297	0.915
S4-4-1	4-20(L)	30.48	297	3.128
S4-4-2	4-20(L)	30.48	297	2.943
C7-1	6-25(L)	30.48	297	1.689 [2]
C5-8-3	6-15(L)	30.48	1033	0.785
C5-8-4	6-15(L)	30.48	1090	0.594
S4-4-3	4-20(L)	30.48	1090	1.992
S4-4-4	4-20(L)	30.48	1090	1.950
C7-2	6-25(L)	30.48	1090	1.067 [2]
C7-3	6-25(L)	30.48	297	2.568

[1] L = LONGITUDINAL CORE RIBBON
W = TRANSVERSE CORE RIBBN

[2] lack of braze fillets across approx. one-half of specimen width.

Brazed Rene' 41 Honeycomb Sandwich Core Shear Tests

Vendor A Foil - As Brazed - Test Type 8

0.533 mm FACE SHEETS

SPECIMEN NUMBER	CORE TYPE [1]	CORE DEPTH (mm)	TEST TEMP K	ULTIMATE LOAD KN	CORE SHEAR STRENGTH MPa
CS11LB-4	6-15(L)	19.05	755	2.04	0.813
CS12LT-4	6-15(L)	19.05	755	2.02	0.806
CS13-LB-4	6-15(L)	19.05	755	2.24	0.896
CS11LB-5	6-15(L)	19.05	922	1.95	0.779
CS12LT-5	6-15(L)	19.05	922	1.86	0.745
CS13LB-5	6-15(L)	19.05	922	1.90	0.758
CS11WB-1B	6-15(W)	19.05	922	1.84	0.738
CS12WT-1B	6-15(W)	19.05	922	1.78	0.710
CS13WB-1B	6-15(W)	19.05	922	2.00	0.800
CS2LB-3	6-15(L)	30.48	922	3.14	0.793
CS2LB-4	6-15(L)	30.48	922	3.19	0.807
CS2LT-5	6-15(L)	30.48	922	3.06	0.772
CS2WB-3	6-15(L)	30.48	922	2.67	0.676
CS2WB-4	6-15(W)	30.48	922	2.71	0.687
CS2WB-5	6-15(W)	30.48	922	2.94	0.633
CS4LB-2	4-15(L)	19.05	922	4.11	1.641
CS5LT-2	4-15(L)	19.05	922	4.11	1.648
CS6LB-2	4-15(L)	19.05	922	4.43	1.772
CS4WB-2	4-15(W)	19.05	922	3.07	1.227
CS5WT-2	4-15(W)	19.05	922	3.25	1.296
CS6WB-2	4-15(W)	19.05	922	2.94	1.172
CS11LB-6	6-15(L)	19.05	1144	1.05	0.418
CS11LB-7	6-15(L)	19.05	1144	1.15	0.461
CS11LB-8	6-15(L)	19.05	1144	1.15	0.461
CS12LT-6	6-15(L)	19.05	1144	1.07	0.429
CS12LT-7	6-15(L)	19.05	1144	1.12	0.447
CS12LT-8	6-15(L)	19.05	1144	1.06	0.423
CS13LB-6	6-15(L)	19.05	1144	1.17	0.466
CS4LB-3	4-15(L)	19.05	1144	2.34	0.938
CS5LT-3	4-15(L)	19.05	1144	2.11	0.848
CS6LB-3	4-15(L)	19.05	1144	2.06	0.820

[1] L = LONGITUDINAL CORE RIBBON
W = TRANSVERSE CORE RIBBON

Brazed Rene' 41 Honeycomb Sandwich Core Shear Tests

Vendor A Foil - As Brazed - Test Type 8

SPECIMEN NUMBER	CORE TYPE [1]	CORE DEPTH mm	TEST TEMP K	ULTIMATE LOAD KN	ULTIMATE SHEAR STRENGTH MPa
CS11LB-1A	6-15(L)	19.05	297	2.30	0.917
CS11LB-1B	6-15(L)	19.05	297	2.41	0.965
CS12LT-1A	6-15(L)	19.05	297	2.28	0.910
CS12LT-15	6-15(L)	19.05	297	2.37	0.945
CS13LB-1A	6-15(L)	19.05	297	2.31	0.924
CS13LB-1B	6-15(L)	19.05	297	2.56	1.020
CS14LB-1A	6-15(L)	19.05	297	2.26	.905
CS14LB-1B	6-15(L)	19.05	297	2.18	.869
CS15LT-1A	6-15(L)	19.05	297	2.30	.917
CS15LT-1B	6-15(L)	19.05	297	2.40	.958
CS11WB-1A	6-15(W)	19.05	297	2.10	.841
CS12WT-1A	6-15(W)	19.05	297	2.14	.855
CS13WB-1A	6-15(W)	19.05	297	2.20	.876
CS14WB-1A	6-15(W)	19.05	297	2.20	.876
CS15WT-1A	6-15(W)	19.05	297	2.38	.917
CS2LB-1A	6-15(L)	30.48	297	3.59	.910
CS2LB-1B	6-15(L)	30.48	297	3.63	.917
CS2LT-2A	6-15(L)	30.48	297	3.69	.931
CS2WB-1A	6-15(W)	30.48	297	2.93	.745
CS2WB-1B	6-15(W)	30.48	297	3.13	.793
CS2WT-2A	6-15(W)	30.48	297	2.87	.724
CS4LB-1A	4-15(L)	19.05	297	4.86	1.944
CS4LB-1B	4-15(L)	19.05	297	5.08	2.027
CS5LT-1A	4-15(L)	19.05	297	5.18	2.068
CS5LT-1B	4-15(L)	19.05	297	5.57	2.227
CS6LB-1A	4-15(L)	19.05	297	5.00	1.999
CS4WB-1A	4-15(W)	19.05	297	3.75	1.503
CS4WB-1B	4-15(W)	19.05	297	3.66	1.462
CS4WB-3	4-15(W)	19.05	297	3.87	1.544
CS4WB-4A	4-15(W)	19.05	297	4.46	1.475 [2]
CS4WB-4B	4-15(W)	19.05	297	4.26	1.420 [2]
CS5WT-1A	4.15(W)	19.05	297	3.70	1.482
CS5WT-1B	4-15(W)	19.05	297	3.81	1.524
CS6WT-1A	4-15(W)	19.05	297	3.77	1.510
CS11LB-3	6-15(L)	19.05	219	2.55	1.020
CS12LT-3	6-15(L)	19.05	219	2.42	.965
CS13LB-3	6-15(L)	19.05	219	2.59	1.034
CS4LB-4	4-15(L)	19.05	219	4.98	1.993
CS5LT-4	4-15(L)	19.05	219	4.92	1.827
CS6LB-4	4-15(L)	19.05	219	5.05	2.020

[1] L = LONGITUDINAL CORE RIBBON
W = TRANSVERSE CORE RIBBON

[2] Specimen 76.2 mm wide

Brazed Rene' 41 Honeycomb Sandwich
Core Shear Tests
Vendor A Foil - Exposed - Test Type 18a
6-15 Core, 0.533 mm Face Sheet, 19.05 mm Core Depth

SPECIMEN NUMBER	CYCLIC CONDITIONS				TEST TEMP. K	ULTIMATE LOAD KN	CORE SHEAR STRENGTH MPa
	STRESS MPa	MAX. TEMP. K	CYCLES #	TIME min.			
CS12LT-2AL	0.088	1033	100	13.5	297	2.58	1.034
CS13LB-2AL	0.088	1033	100	13.5	297	2.49	0.993
CS15LT-2L	0.088	1033	100	13.5	297	2.38	0.951
CS13LB-2BL	0.088	1033	100	13.5	922	2.11	0.848
CS15LT-3L	0.088	1033	100	13.5	922	2.03	0.814
CS15LT-4L	0.088	1033	100	13.5	922	2.09	0.834
CS12LT-2BL	0.088	1033	100	13.5	1144	1.19	0.477
CS13LB-7L	0.088	1033	100	13.5	1144	1.14	0.456
CS15LT-5L	0.088	1033	100	13.5	1144	1.12	0.448
CS12LT-9M	0.088	1033	500	13.5	1144	1.19	0.475
CS13LB-8M	0.088	1033	500	13.5	1144	1.04	0.414
CS15LT-6M	0.088	1033	500	13.5	1144	1.23	0.491

Brazed Rene' 41 Honeycomb Panel Core Shear

Vendor B Foil Residual Strength Testing, Exposed - Test Type 18b

0.533 mm Face Sheet, 30.48 mm Core Depth

THERMAL EXPOSURE, 13.5 MIN CYCLES			CORE TYPE	TEST TEMPERATURE			RESIDUAL ULT STRENGTH, MPa	
				70°F	1400°F	1500°F		
STRESS (MPa)	MAX. TEMP. K	CYCLES		294K	1033K	1089K	R. TEMP	ELEV TEMP
0.296	1033	100	6-15	C5-1-1	C5-1-3		0.679*	0.701
		100	6-15	C5-1-2	C5-1-4		0.703*	0.688
		144	6-15	C5-5-1			0.876	-
		144	6-15	C5-5-2			0.869	-
0.148	1033	100	6-15	C5-2-1	C5-2-3		0.838	0.695
		100	6-15	C5-2-2	C5-2-4		0.934	.741
		47	6-15	C5-4-1	C5-4-3		0.983	.780
		47	6-15	C5-4-2	C5-4-4		.938	.618
		500	6-15	C5-6-1	C5-6-3		.947	.562
		500	6-15	C5-6-2	C5-6-4		.861	.627
0.138	1090	100	6-15	C6-8-1		C6-8-3	.816	.523
		100	6-15	C6-8-2		C6-8-4	.886	.558
		200	6-15	C6-3-1		C6-3-3	.792	.463
		200	6-15	C6-3-2		C6-3-4	.829	.435
		500	6-15	C6-5-1		C6-5-3	.829	.520
		500	6-15	C6-5-2		C6-5-4	.776	.478
0.069	1090	100	6-15	C6-2-1		C6-2-3	.869	.476
		100	6-15	C6-2-2		C6-2-4	.876	.558
		200	6-15	C6-6-1		C6-6-3	.916	.590
		200	6-15	C6-6-2		C6-6-4	.890	.574
		500	6-15	C6-1-1		C6-1-3	.834	.541
		500	6-15	C6-1-2		C6-1-4	.854	.532
0.276	1090	100	4-20	S4-1-1		S4-1-3	3.034	1.892
		100	4-20	S4-1-2		S4-1-4	2.993	1.863
		200	4-20	S4-2-1		S4-1-3	3.174	1.846
		200	4-20	S4-2-2		S4-1-4	3.039	1.812
		500	4-20	S4-3-1		S4-3-3	3.185	1.900
		500	4-20	S4-3-2		S4-3-4	3.089	1.985
		500	6-25	S7-C6-1-1		S7-C6-1-3	2.321	1.351
		500	6-25	S7-C6-1-2		S7-C6-1-4	2.440	1.213
0.228	1090	100	6-25	S7-C6-2-1		S7-C6-2-3	2.440	1.451
		100	6-25	S7-C6-2-2		S7-C6-2-4	2.428	1.464
		200	6-25	S7-C6-3-1		S7-C6-3-3	2.397	1.451
		200	6-25	S7-C6-3-2		S7-C6-3-4	2.368	1.457
		500	6-25	S7-C6-4-1		S7-C6-4-3	2.368	1.399
		500	6-25	S7-C6-4-2		S7-C6-4-4	2.457	1.231

*CORE CRUSH AT LOAD HEAD

Brazed Rene' 41 Honeycomb Sandwich Creep Deflection

During Thermal Exposure

13.5 Min. Cycle, 30.48cm Span, 3 Point Load, Vendor B Foil

SPEC. NO.	APPLIED STRESS(kPa)	PEAK CYCLIC TEMP. (K)	NO. OF CYCLES							
			25	50	75	100	200	300	400	500
			MID-SPAN DEFLECTION(mm)							
A	414	1090	11.43 [1]	–	–	–	–	–	–	–
B	207	1090	3.07	5.5 [2]	–	–	–	–	–	–
C	138	1090	2.54	3.17	3.81	4.02	7.83	12.7 [3]	–	–
C5-6	148	1033	0.38	–	0.64	0.76	2.03	2.34	2.67	2.84
C5-1	297	1033	1.19	2.16	3.18	3.94	–	–	–	–
C6-1	70	1090	–	–	–	0.56 [4]	1.19	1.35	1.75 [5]	2.08
C6-3	138	1090	0.76	1.70	2.29	3.18	5.33	–	–	–
C6-8	138	1090	–	–	–	2.29	–	–	–	–
C6-5	138	1090	–	–	–	2.29	–	–	5.46	6.48
S4-1	276	1090	0.25	0.50	0.97	0.97	–	–	–	–
S7-1	276	1090	–	–	–	–	–	–	–	2.29
S7-4	228	1090	–	–	–	–	–	–	–	0.76

[1] ½ CYCLE

[2] LOCAL CRUSHING UNDER LOAD HEAD

[3] 280 CYCLES

[4] 107 CYCLES

[5] 338 CYCLES

Brazed Rene' 41 Honeycomb Sandwich

Edgewise Compression Tests

Vendor A Foil - As Brazed - Test Type 9

SPECIMEN NUMBER	CORE [1] DIRECTION	SKIN GAGE (mm)	TEST TEMP K	ULTIMATE LOAD KN	SKIN STRESS GPa
E7L-1	L	.279	297	38.7	.909
E7L-2	L	.279	297	35.3	.829
E7L-3	L	.279	297	35.0	.822
E7L-4	L	.279	297	33.9	.797
E8L-1	L	.279	297	36.3	.852
E8L-2	L	.279	297	37.6	.884
E8L-3	L	.279	297	36.6	.858
E9L-1	L	.279	297	35.3	.829
E9L-2	L	.279	297	35.6	.835
E9L-3	L	.279	297	36.7	.863
E10L-1	L	.279	297	36.4	.851
E12W-1	W	.533	297	77.7	.956
E13W-1	W	.533	297	72.8	.896
E14W-1	W	.533	297	73.3	.901
E14W-2	W	.533	297	71.3	.877
E15W-1	W	.533	297	67.9	.835
E7L-12	L	.279	.219	37.8	.887
E8L-12	L	.279	.219	38.6	.906
E9L-12	L	.279	.219	36.7	.862
E7L-9	L	.279	755	34.6	.813
E10L-2	L	.279	755	34.6	.812
E9L-9	L	.279	755	36.1	.847
E7L-10	L	.279	922	31.8	.748
E10L-3	L	.279	922	30.7	.722
E9L-10	L	.279	922	31.8	.747
E14W-3	W	.533	922	15.4	.190
E14W-4	W	.533	922	60.2	.740
E15W-2	W	.533	922	59.8	.736
E7L-11	L	.279	1144	14.1	.332
E8L-11	L	.279	1144	14.2	.334
E9L-11	L	.279	1144	14.4	.339
E14W-5	W	.533	1144	30.4	.374
E14W-6	W	.533	1144	28.3	.348
E15W-3	W	.533	1144	28.0	.344

6-15 CORE, 19.05 mm CORE DEPTH

[1] L = LONGITUDINAL CORE RIBBON
W = TRANSVERSE CORE RIBBON

Brazed Rene' 41 Honeycomb Sandwich

Edgewise Compression Tests

Vendor A Foil – Exposed – Test Type 19

6-15 Core, 0.279 mm Skin, 19.05 mm Core Depth

SPECIMEN NUMBER	CYCLIC CONDITIONS				TEST TEMP K	ULTIMATE LOAD KN	SKIN STRESS GPa
	STRESS MPa	MAX TEMP K	CYCLES #	TIME min.			
E8L-9H	68.9	1033	100	13.5	297	37.8	0.887
E9L-5H	68.9	1033	100	13.5	297	39.7	0.933
E10L-4H	68.9	1033	100	13.5	297	35.5	0.834
E8L-10H	68.9	1033	100	13.5	755	36.6	0.858
E9L-8H	68.9	1033/1144	100/7	13.5	755	35.1	0.825
E10L-5H	68.9	1033	100	13.5	755	33.5	0.787
E8L-7H	68.9	1033	100	13.5	922	30.7	0.721
E9L-7H	68.9	1033/1144	100/7	13.5	922	31.0	0.727
E10L-6H	68.9	1033	100	13.5	922	30.4	0.714
E8L-8H	68.9	1033	100	13.5	1144	14.7	0.344
E9L-6H	68.9	1033	100	13.5	1144	13.5	0.318
E10L-7H	68.9	1033	100	13.5	1144	12.8	0.302

0.533 mm Skin, Vendor B Foil as Brazed – Test Type 9
30.48 mm Core

SPECIMEN NUMBER	CORE TYPE	TEST TEMP. K	ULTIMATE STRENGTH GPa
E7-1B	6-25	297	0.904
E2-1A	6-15	297	0.913
E3-1A	6-15	297	0.773
E3-16A	6-15	297	0.927
E3-17A	6-15	297	0.955
E1-6A	6-15	1033	0.696
E2-3A	6-15	1033	0.721
E2-3B	6-15	1033	0.722
E1-6B	6-15	1090	0.612
E2-18A	6-15	1090	0.552
E3-16B	6-15	1090	0.575
E2-18B	6-15	1144	0.391
E3-17B	6-15	1144	0.414

Edgewise Compression

Residual Strength Testing

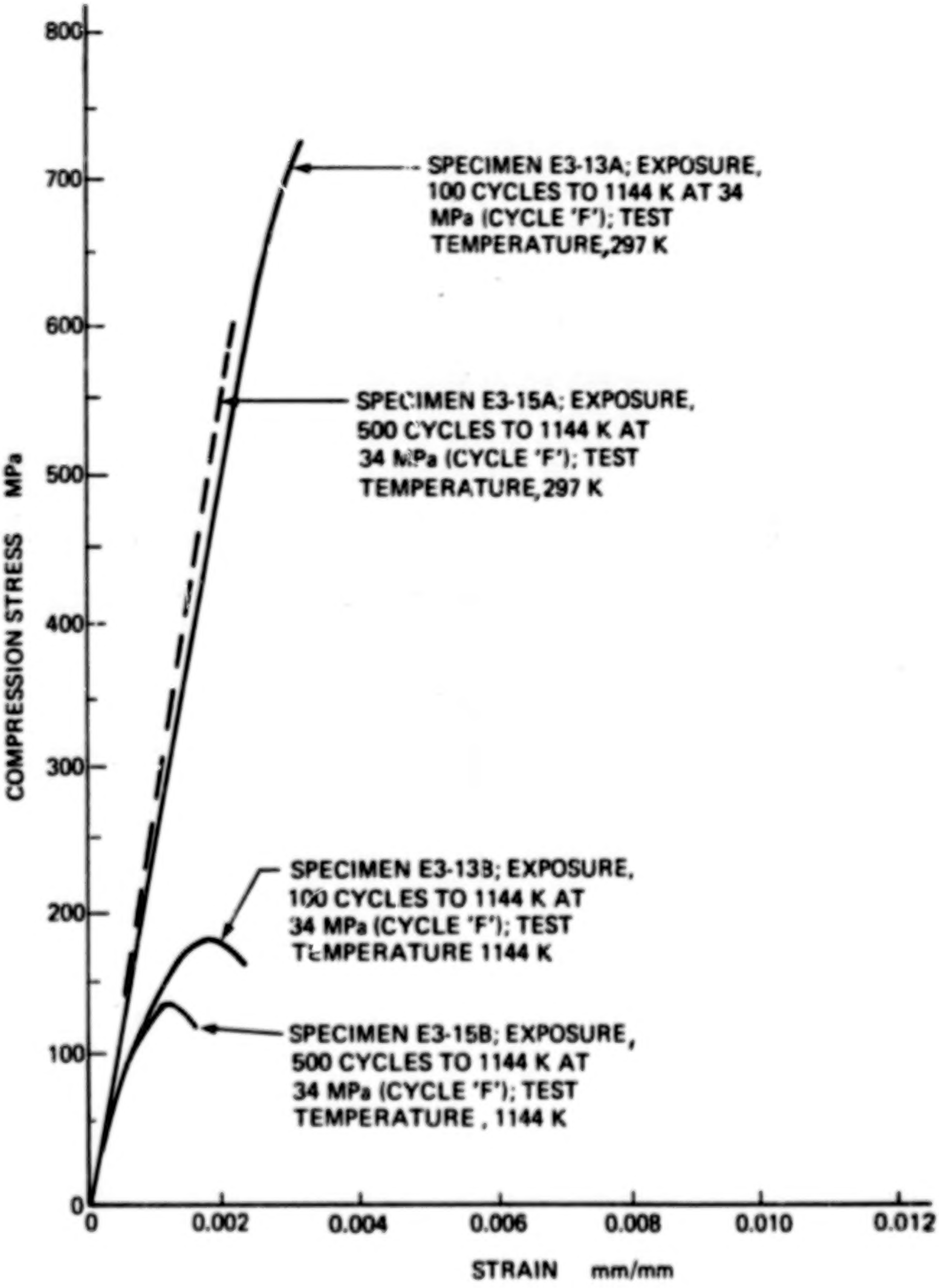
Vendor B Foil, Exposed - Test Type 19

0.533 mm Face Sheet, 30.48 mm Core Depth

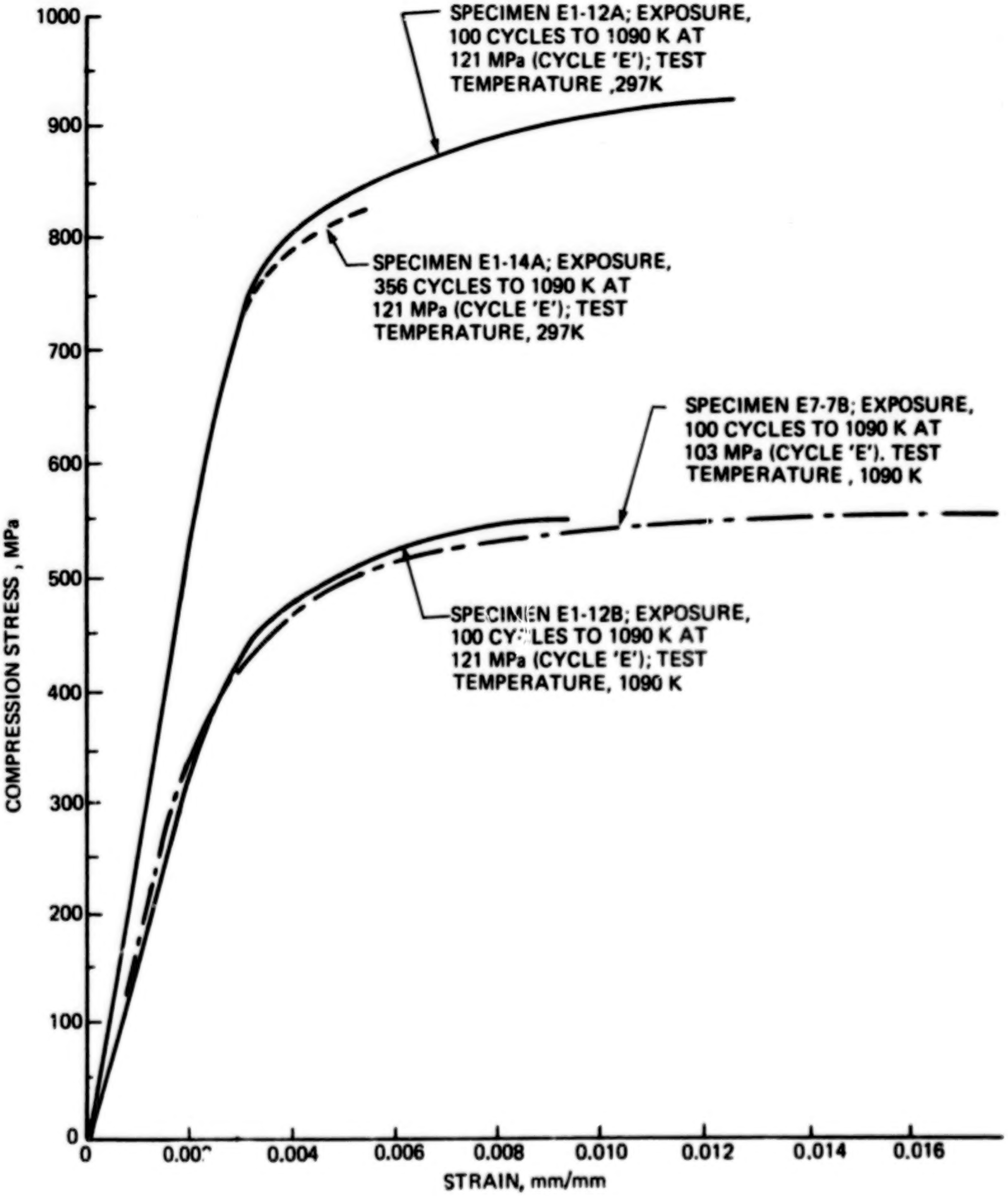
THERMAL EXPOSURE, 13.5 min cycles			CORE TYPE	TEST TEMPERATURE, K				RESIDUAL ULT STRENGTH, GPa	
STRESS MPa	MAX. TEMP.	CYCLES		297	1033	1090	1144	R. TEMP	ELEV. TEMP
172	1033K	100	6-15	E1-5A	E1-5B			0.951	0.735
172		100	6-15	E3-7A	E3-7B			0.961	.638
172		200	6-15	E1-2B	E1-2A			0.920	.734
310,241		100, 99	6-15	E1-3A	E3-8A			0.969	.638
121		95	6-15	E3-9A	E3-9B			—	—
121	1033K	100	6-15	E1-7A	E1-7B			0.936	.598
121		100	6-15	E3-4A	E3-4B			0.889	.731
121		200	6-15	E1-8A	E1-8B			0.963	.601
121		200	6-15	E3-5A	E3-5B			0.927	.730
121		500	6-15	E1-9A	E1-9B			0.920	.696
121		500	6-15	E3-6A	E3-6B			0.927	.590
241	1090K	6	6-15	E2-17A		E2-17B		0.917	.541
241, 241		12, 6	6-15	E1-10B		E2-4B		0.926	.574
103		200	6-15	E2-8A		E2-8B		0.863	.327
103		484	6-15	E1-13A		E1-13B		0.498	.159
241, 241		12, 17	6-15	E2-5A		E2-16A		0.918	.494
121	1090K	100	6-15	E1-12A		E1-12B		0.929	.554
121		200	6-15	E1-11A		E1-11B		0.855	.441
121		356	6-15	E1-14A				0.829	
121		492	6-15	E1-15A		E1-15B		—	—
69	1144K	100	6-15	E2-10A			E2-10B	.760	.328
52		100	6-15	E3-10A			E3-10B	.822	.259
52		200	6-15	E2-11A			E2-11B	.462	.183
52		200	6-15	E3-11A			E3-11B	.727	.265
52		500	6-15	E3-12A			E3-12B	.555	.158
34	1144K	100	6-15	E2-13A			E2-13B	.848	.375
34		100	6-15	E3-13A			E3-13B	.735	.183
34		200	6-15	E2-14A	E3-14B		E2-14B	.696	.340
34		200	6-15	E3-14A	[2]			.827	.579
34		500	6-15	E2-15A			E2-15B	.526	.263
34		500	6-15	E3-15A			E3-15B	.607	.137
103	1090K	[1]	6-25	E7-2A		E7-2B		.951	.583
103		100	6-25	E7-4A		E7-4B		.916	.604
103		200	6-25	E7-5A		E7-5B		.954	.592
103		200	6-25	E7-7A		E7-7B		.866	.564
103		360	6-25			E7-8B			.554
0.0	1144K	500	6-15	E3-18A			E3-18B	.681	.193

[1] 85 cycles plus 8 hour soak

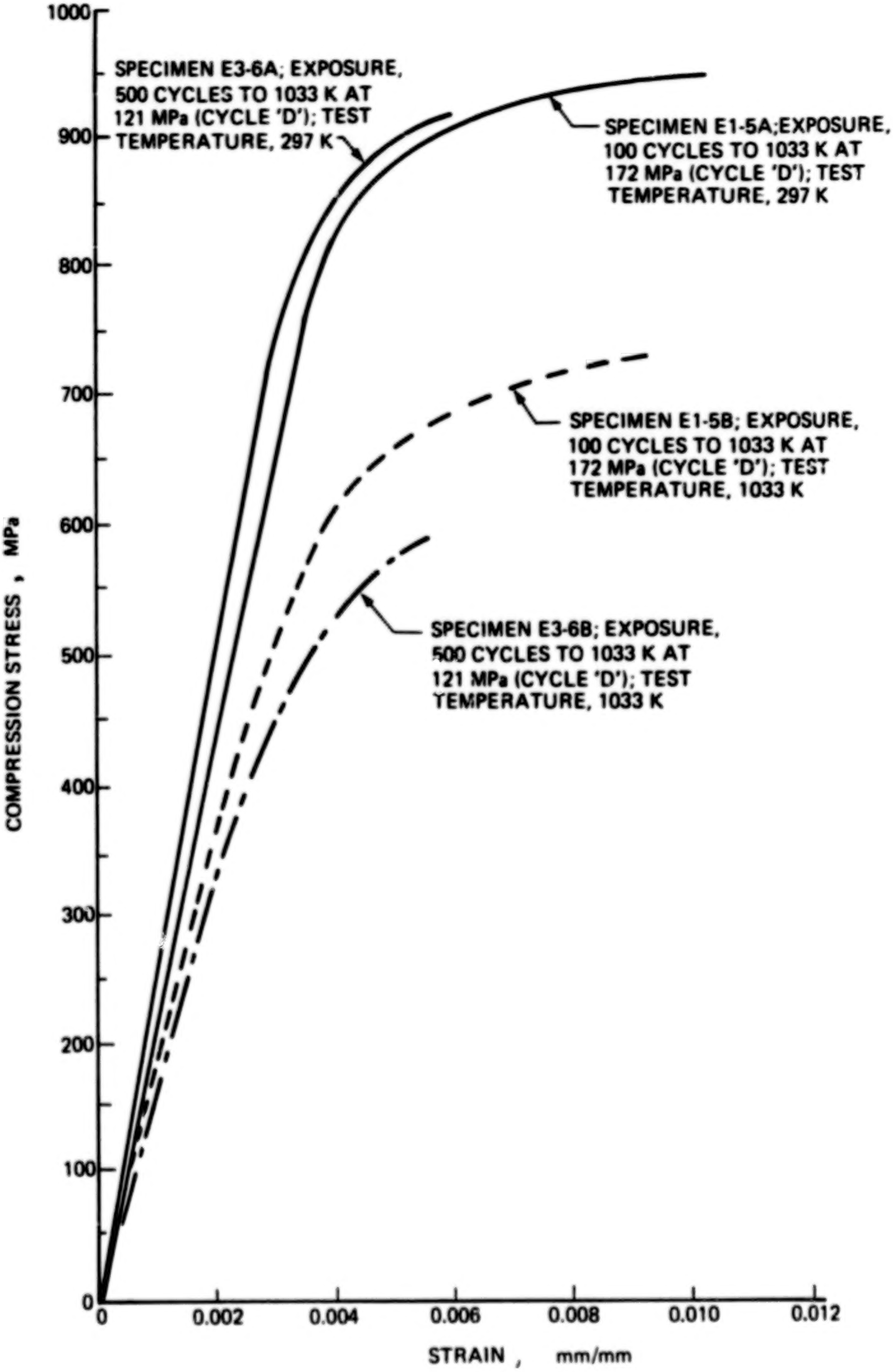
[2] Operator error, test planned at 1144K



EWC STRESS-STRAIN CURVES



EWC STRESS-STRAIN CURVES



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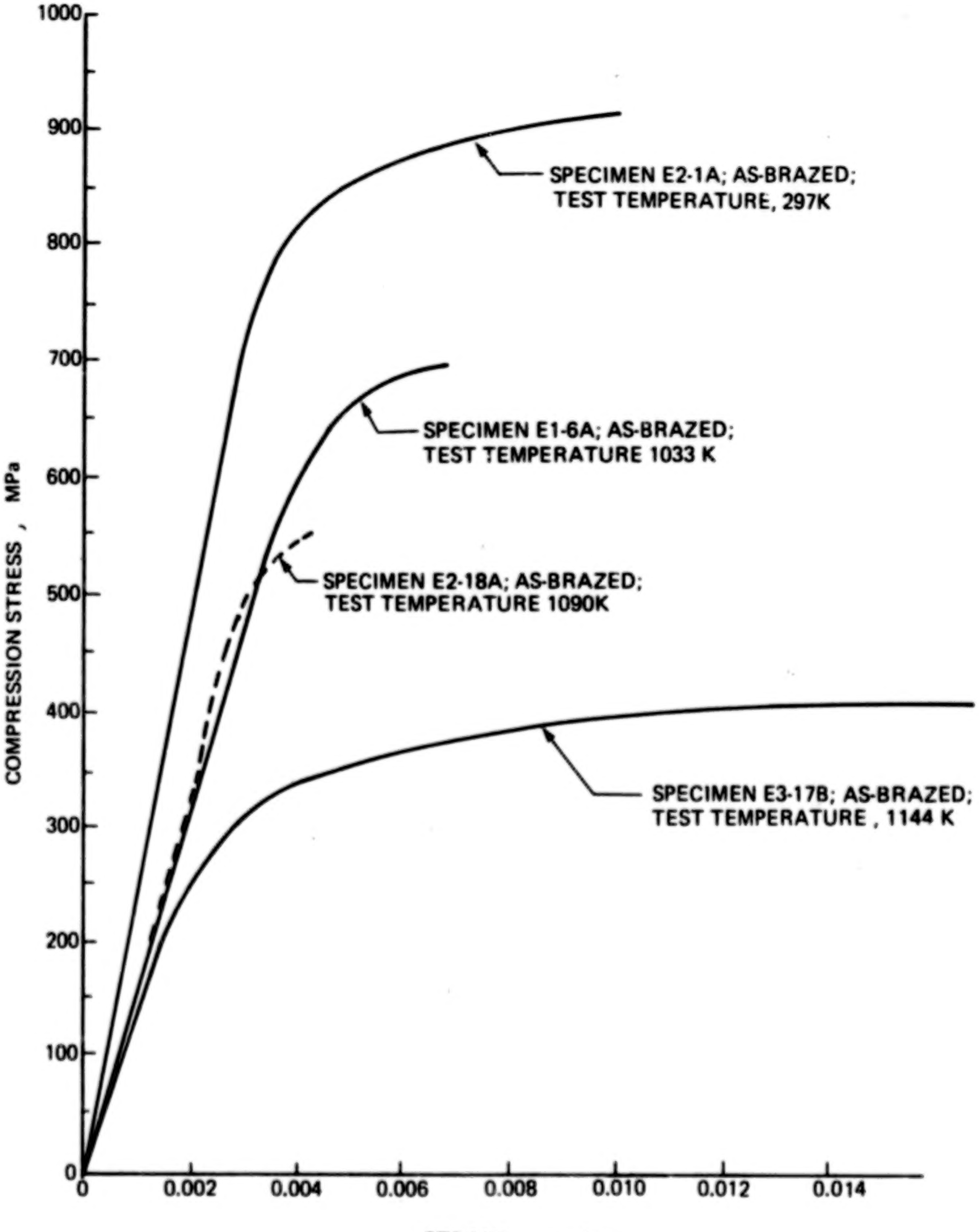


EWC STRESS-STRAIN CURVES

Brazed Rene' 41 Honeycomb Sandwich

Vendor A Foil - Barrel Compression Tests - Test Type 20

6-15 Core, 0.483 mm Skin Gage

SPECIMEN NUMBER	CYCLIC CONDITIONS STRESS MPa	MAX TEMP K	CYCLES #	TIME min	TEST TEMP K	ULTIMATE LOAD KN	SKIN STRESS GPa
B17-6H	75.842	1033	100	13.5	297	71.26	0.972
B18-5H	75.842	1033	100	13.5	297	68.99	0.928
B21-3H	75.842	1033	100	13.5	297	71.53	0.972
B22-3H	75.842	1033	100	13.5	297	70.82	0.965
B23-5H	75.842	1033	100	13.5	297	70.90	0.965
B18-6H	75.842	1033	100	13.5	755	64.68	0.883
B21-4H	75.842	1033	100	13.5	755	67.08	0.910
B21-7H	75.842	1033	100	13.5	755	67.88	0.924
B22-4H	75.842	1033	100	13.5	755	67.36	0.917
B23-6H	75.842	1033	100	13.5	755	67.84	0.924
B18-7H	75.842	1033	100	13.5	922	47.68	[1] 0.648
B21-5H	75.842	1033	100	13.5	922	62.85	0.855
B22-5H	75.842	1033	100	13.5	922	61.61	0.834
B22-7H	75.842	1033	100	13.5	922	62.32	0.848
B23-7H	75.842	1033	100	13.5	922	64.72	0.883
B17-7H	75.842	1033	100	13.5	1144	25.44	[2] 0.346
B18-8H	75.842	1033	100	13.5	1144	27.31	0.372
B21-6H	75.842	1033	100	13.5	1144	24.69	[2] 0.336
B22-6H	75.842	1033	100	13.5	1144	25.31	[2] 0.344
B23-8H	75.842	1033	100	13.5	1144	23.26	[2] 0.316

[1] QUESTIONABLE DATA

[2] PREMATURE FAILURE AT END OF SPECIMEN

Brazed Rene' 41 Honeycomb Sandwich
Barrel Compression Tests
6-15 Core, 0.483 mm Skin Gage
Vendor A Foil - As Brazed

SPECIMEN NUMBER	CORE TYPE	TEST TEMP K	ULTIMATE LOAD KN	SKIN STRESS GPa
B24-1	4-15	297	85.3	1.16
B24-2	4-15	297	83.1	1.13
B25-1	4-15	297	29.9	[1]
B25-2	4-15	297	74.9	1.02
B26-1	4-15	297	79.2	1.08
B17-1	6-15	297	68.7	.93
B18-1	6-15	297	66.4	.90
B21-1	6-15	297	61.8	.84
B22-1	6-15	297	67.7	.92
B23-1	6-15	297	68.2	.93
B17-2	6-15	219	68.9	.94
B21-2	6-15	219	68.9	.94
B22-2	6-15	219	69.5	.94
B17-3	6-15	755	62.7	.85
B18-2	6-15	755	59.2	.81
B23-2	6-15	755	62.0	.84
B24-3	4-15	922	74.9	1.02
B25-3	4-15	922	74.1	1.01
B26-2	4-15	922	71.4	.97
B17-4	6-15	922	55.8	.76
B18-3	6-15	922	58.7	.80
B23-2	6-15	922	59.1	.81
B17-5	6-15	1144	21.6	.29 [2]
B18-4	6-15	1144	21.7	.29 [2]
B23-4	6-15	1144	24.2	.33

[1] POOR SPECIMEN DUE TO SKIN/CORE SEPARATION DURING BRAZING

[2] PREMATURE FAILURE DUE TO DEGRADATION OF CORE ADJACENT TO POTTING COMPOUND

APPENDIX B

SPECIMEN IDENTIFICATION CODES

TABLE B-1: CODING SYSTEM FOR SPECIMENS FABRICATED WITH VENDOR A CORE FOIL

BRAZED RENE'41 DESIGN DATA

SPECIMEN TYPE
PANEL NO.
SKIN LOCATION OR RIBBON DIRECTION
SERIAL NO.

SPECIMEN NO.: X X X - X

SPECIMEN TYPE:

T	FACE TENSION - BASEMETAL
TB	FACE TENSION - BRAZE CYCLE
LB	LONG BEAM FLEXURE
CS	CORE SHEAR
C	FACE COMPRESSION - BASEMETAL
CB	FACE COMPRESSION - BRAZE CYCLE
E	EDGEWISE COMPRESSION
B	BARREL COMPRESSION
F	FLATWISE TENSION
CC	CORE COMPRESSION
P	PEEL
ER	EDGEWISE COMPRESSION, 2ND FOIL LOT

PANEL:

NO.	NOM. SKIN GAGE, mm(in.)	CORE TYPE	CORE DEPTH, mm(in.)
1,2	0.50(0.020)	6-15	30.48(1.20)
3-6	0.50(0.020)	4-15	19.05(0.75)
7-10	0.25(0.010)	6-15	19.05(0.75)
11-16	0.50(0.020)	6-15	19.05(0.75)
17-23	0.50(0.020)	6-15	12.7-30.48(0.5-1.2)
24-26	0.50(0.020)	6-15	12.7-30.48(0.5-1.2)
ER	SPECIMENS 0.50(0.020)	6-25	30.48(1.20)

SKIN LOCATION OR RIBBON DIRECTION:

T	TOP SKIN
B	BOTTOM SKIN
LT	LONGITUDINAL RIBBON TOP SKIN IN TENSION
WT	TRANSVERSE RIBBON, TOP SKIN IN TENSION
LB	LONGITUDINAL RIBBON, BOTTOM SKIN IN TENSION
WB	TRANSVERSE RIBBON, BOTTOM SKIN IN TENSION

SERIAL NO. (NO.) INDIVIDUAL SERIAL NO.

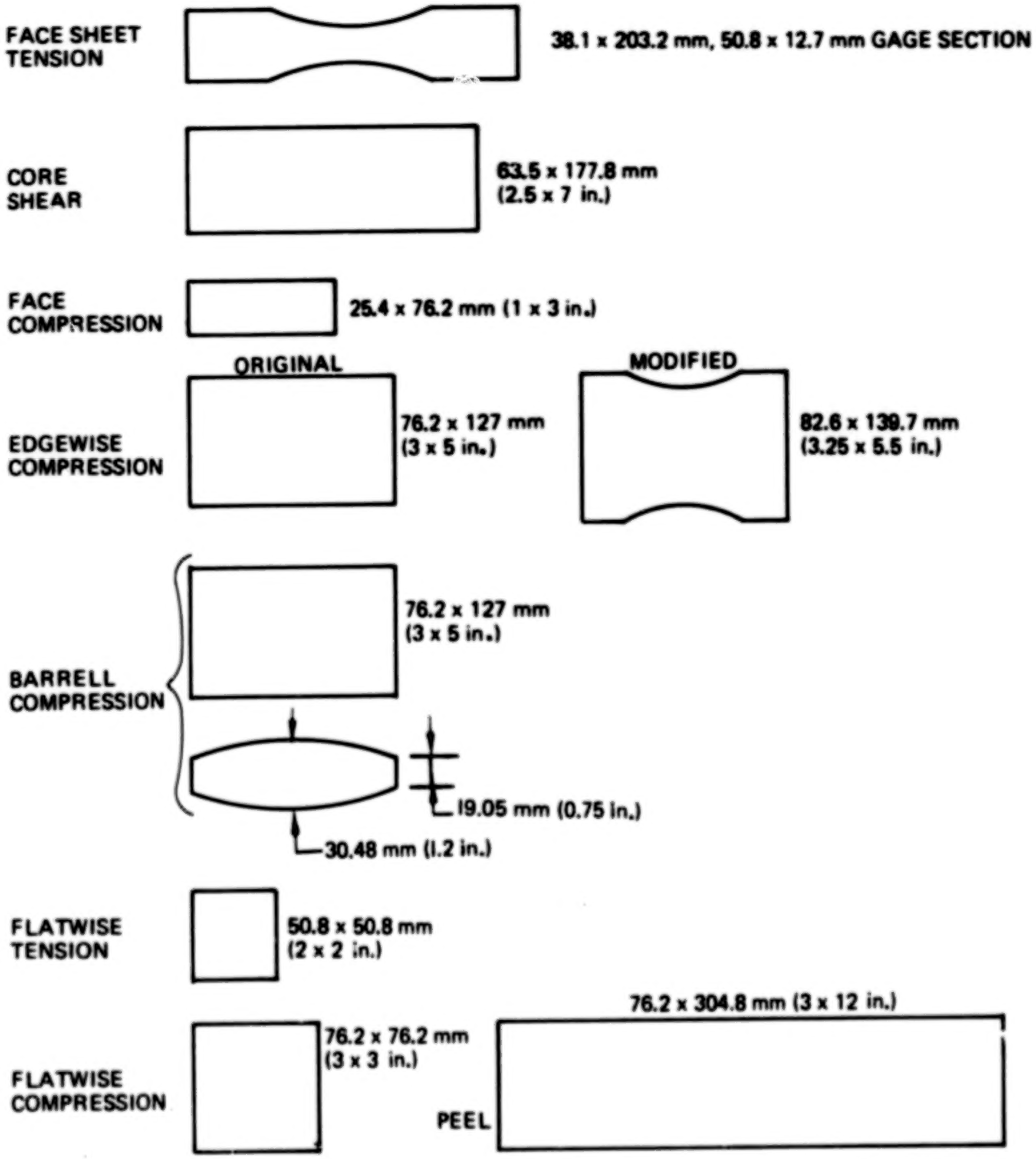

FACE SHEET TENSION
38.1 x 203.2 mm, 50.8 x 12.7 mm GAGE SECTION
CORE SHEAR
63.5 x 177.8 mm
(2.5 x 7 in.)
FACE COMPRESSION
25.4 x 76.2 mm (1 x 3 in.)
ORIGINAL
MODIFIED
EDGEWISE COMPRESSION
76.2 x 127 mm
(3 x 5 in.)
82.6 x 139.7 mm
(3.25 x 5.5 in.)
BARRELL COMPRESSION
76.2 x 127 mm
(3 x 5 in.)
19.05 mm (0.75 in.)
30.48 mm (1.2 in.)
FLATWISE TENSION
50.8 x 50.8 mm
(2 x 2 in.)
FLATWISE COMPRESSION
76.2 x 76.2 mm
(3 x 3 in.)
PEEL
76.2 x 304.8 mm (3 x 12 in.)

Figure B-1: Specimen Configurations

TABLE B-2: CODING SYSTEM FOR SPECIMENS
FABRICATED WITH VENDOR B CORE FOIL

SPECIMEN TYPE:	TT	FACE SHEET TENSION OR FACE SHEET CREEP, TOP FACE
	TB	FACE SHEET TENSION OR FACE SHEET CREEP, BOTTOM FACE
	E	EDGEWISE COMPRESSION
	S	CORE SHEAR
	C	CORE SHEAR

PANEL:	NO.	NOM. SKIN GAGE, mm (in.)	CORE TYPE	CORE DEPTH, mm (in.)
	1-3	0.050(0.020)	6-15	30.48(1.20)
	4	0.050(0.020)	4-20	30.48(1.20)
	5,6	0.050(0.020)	6-15	30.48(1.20)
	7	0.050(0.020)	6-25	30.48(1.20)

SERIAL NO. INDIVIDUAL ALPHANUMERIC SERIAL NUMBER

APPENDIX C

Preliminary Face Sheet Tension Testing

The static mechanical design properties for braze Rene'41 material heat treated to the braze thermal cycle were initially estimated from a limited amount of IR&D data for brazed 0.762 mm (0.030 in.) Rene'41 material. The compression yield was assumed to be equal to the tensile yield and the shear ultimate was assumed to be 60% of the tensile ultimate. The properties of the 0.279 mm (0.011 in.) material were reduced to account for the effect of thickness on the tensile properties seen for other Rene'41 heat treatments. The estimated properties are shown in Figure C-1.

Base metal tensile control specimens for both skin gages were fabricated and subjected to the braze thermal cycle but without the braze alloy. The 0.533 mm (0.021 in.) base metal tensile properties (F_{tu}, F_{ty}, and elongation) were found to be essentially equivalent to the initial estimates. The 0.279 mm (0.011 in.) F_{tu} values were about 10% higher than the estimated values, the elongation was about as predicted, but the F_{ty} values were lower than estimated. These results are shown by the open symbols in Figures C-2 for 0.279 mm (0.01 in.) and C-3 for 0.533 mm (0.02 in.) compared with the preliminary estimates repeated from Figure C-1.

Tensile data for specimens cut from the honeycomb sandwich faces were also obtained to evaluate the influences of the braze alloy and brazing process on the mechanical properties. These data are plotted as the solid symbols in Figures C-2 and C-3. The thickness of the braze alloy was neglected in calculating the tensile stresses and the braze fillets were machined off. The data for the 0.279 mm (.011 in.) brazed faces showed a moderate decrease in the ultimate

APPENDIX C

PRELIMINARY FACE SHEET TENSION TESTING

Concurrently with the above investigation on specimen configurations, a series of specimens were exposed to thermal cycling. Figure C-5 shows the residual strength and elongation values after cycling. Specimens for these tests were cut from a brazed honeycomb sandwich panel and had the braze fillets machined off but retained the braze alloy on the sheet. Each point plotted in Figure C-5 is the average of three test points. These data show only minor changes in tensile ultimate and tensile yield properties out to 500 thermal cycles, however, there is a reduction of elongation properties after about 100 cycles.

strength and a severe decrease in elongation with an increase in the yield strength at all test temperatures. The data for the 0.533 mm (0.021 in.) brazed faces also showed a decrease in the ultimate strength and elongation, while the yield strength did not increase.

Supplemental investigations were conducted to establish an explanation for the low elongation of the as-brazed Rene'41 sheet material. Metallurgical studies showed an inter-diffusion of the Rene'41 and the AMI 930 FOB braze alloy, but no conclusions could be drawn about the impact of this interdiffusion on the tensile properties. The effect of various tensile specimen configurations were investigated using the 0.279 mm (0.011 in.) material. The average test results for several specimen configurations are shown in Figure C-4. The specimens with no braze alloy were base metal Rene'41 specimens heat treated to the braze cycle. The specimens with braze alloy off were cut from a brazed honeycomb sandwich panel and had the braze alloy and braze fillets completely machined off down to the base metal. These tests showed a decrease in elongation from 24% down to 9.5% due to the braze alloy having been present on the material during the braze thermal cycle. The specimens with the braze alloy on, without and with fillets, were cut from the same brazed honeycomb sandwich panel as the previous specimens. The elongation values for these specimens were even lower. These results indicate both a metallurgical influence and a geometric influence of the braze alloy on the specimen tensile properties. Based upon these studies, it was concluded that all further tensile testing should be conducted using specimens cut from brazed honeycomb sandwich panels with the braze fillets left intact in order to obtain design data directly applicable to sandwich panels.

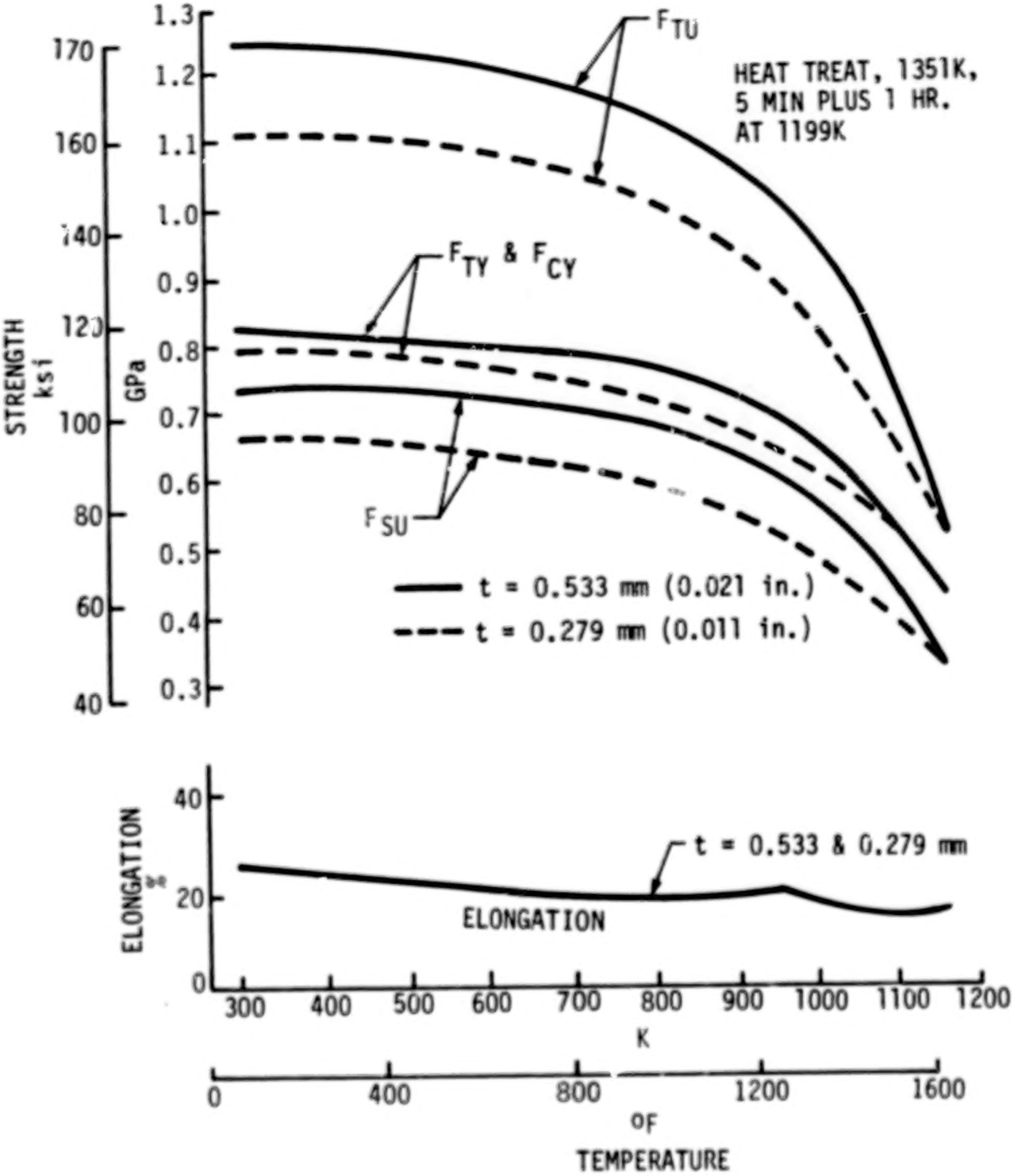


Figure C-1: Estimated Base Metal Properties.

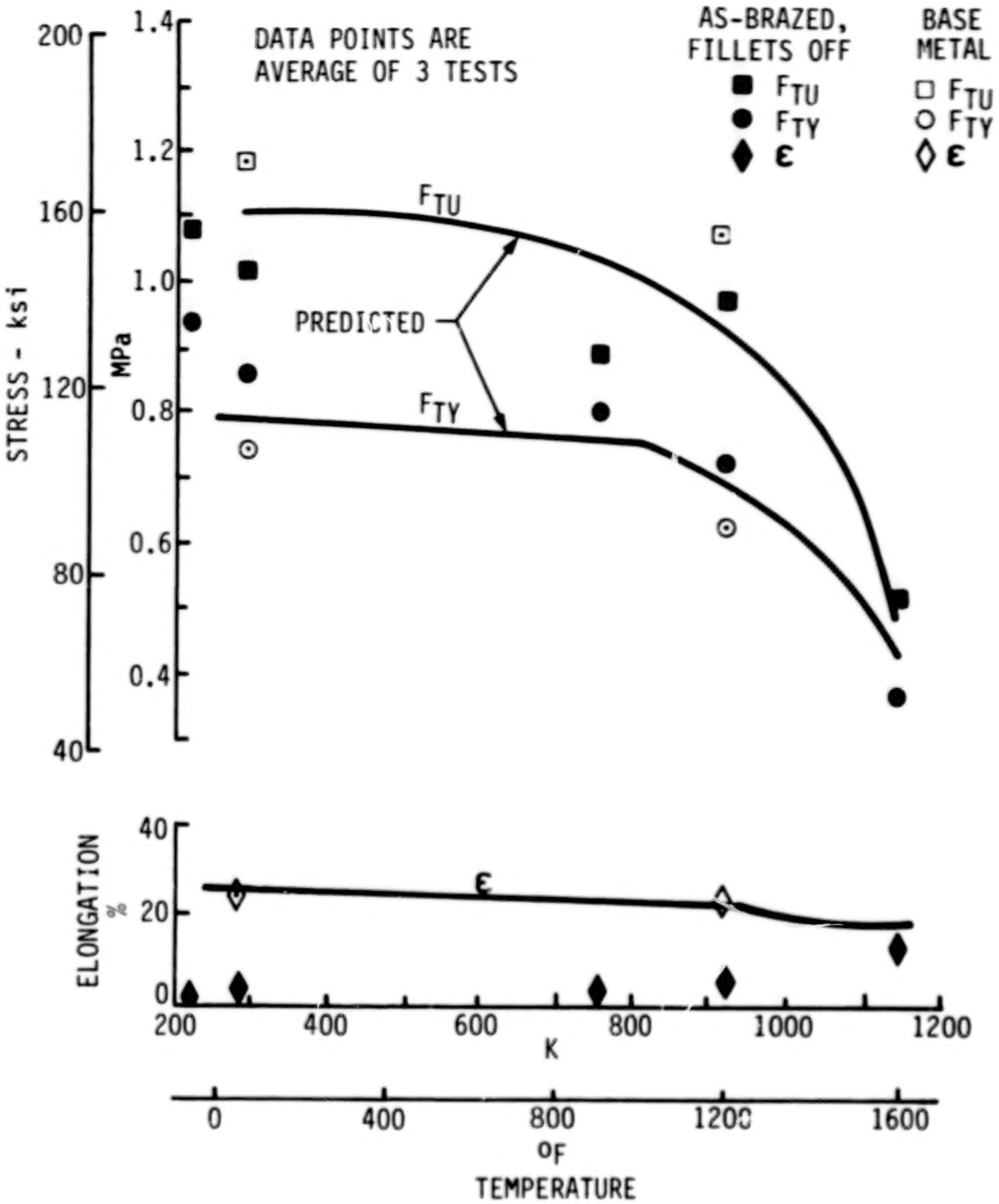


Figure C-2

Tensile Predictions and Test Data vs Temperature, 0.0279 mm Face Sheet.

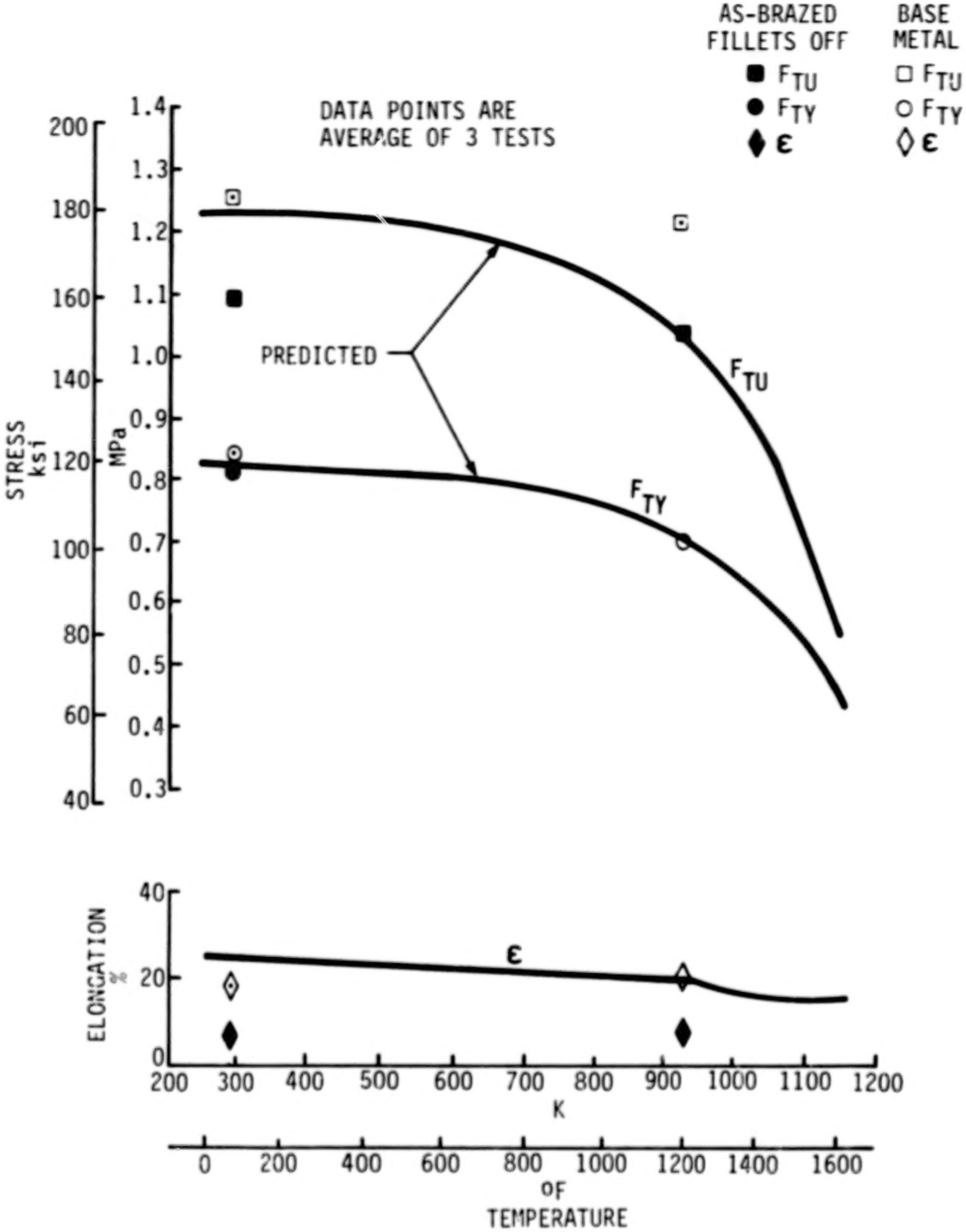
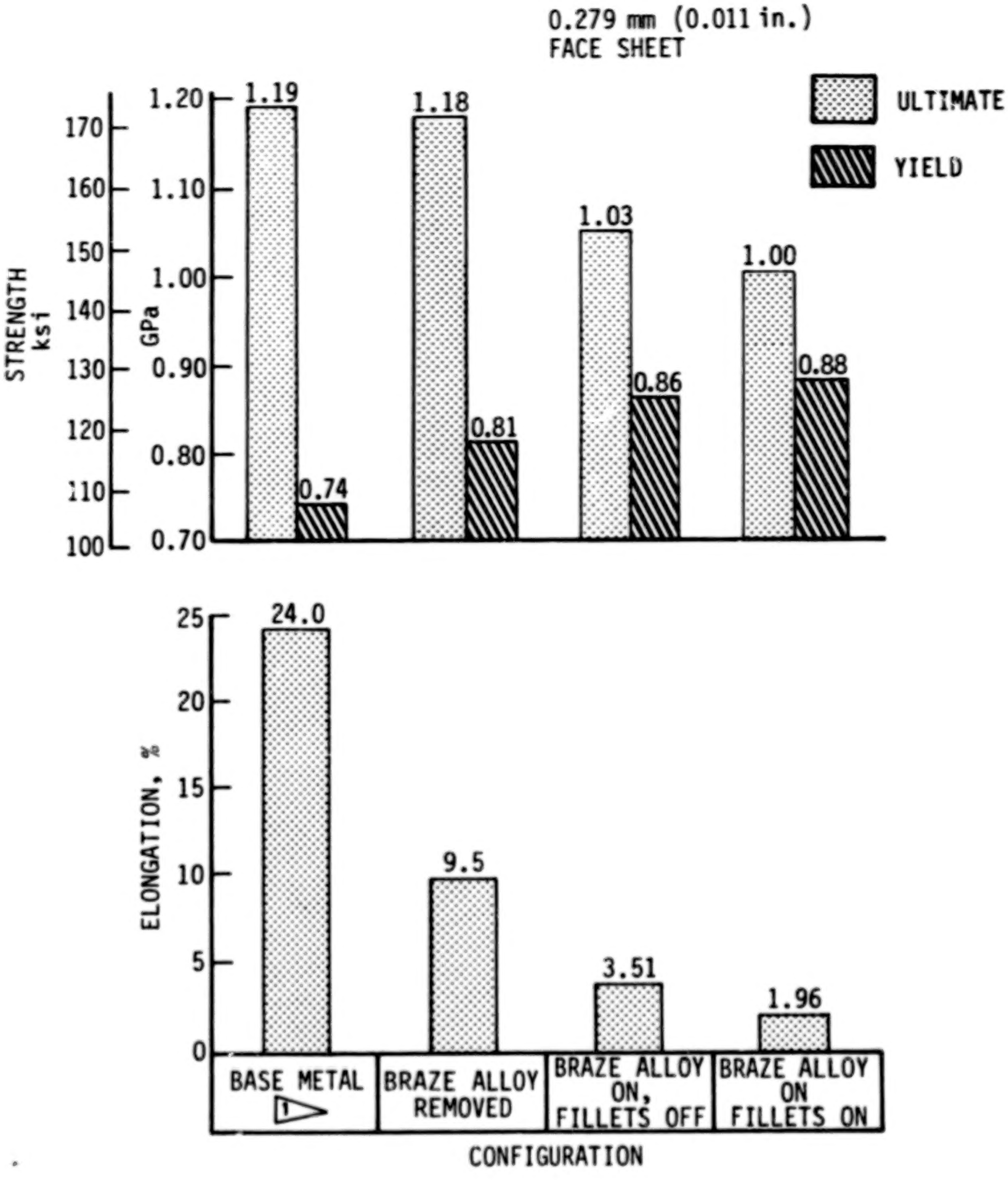
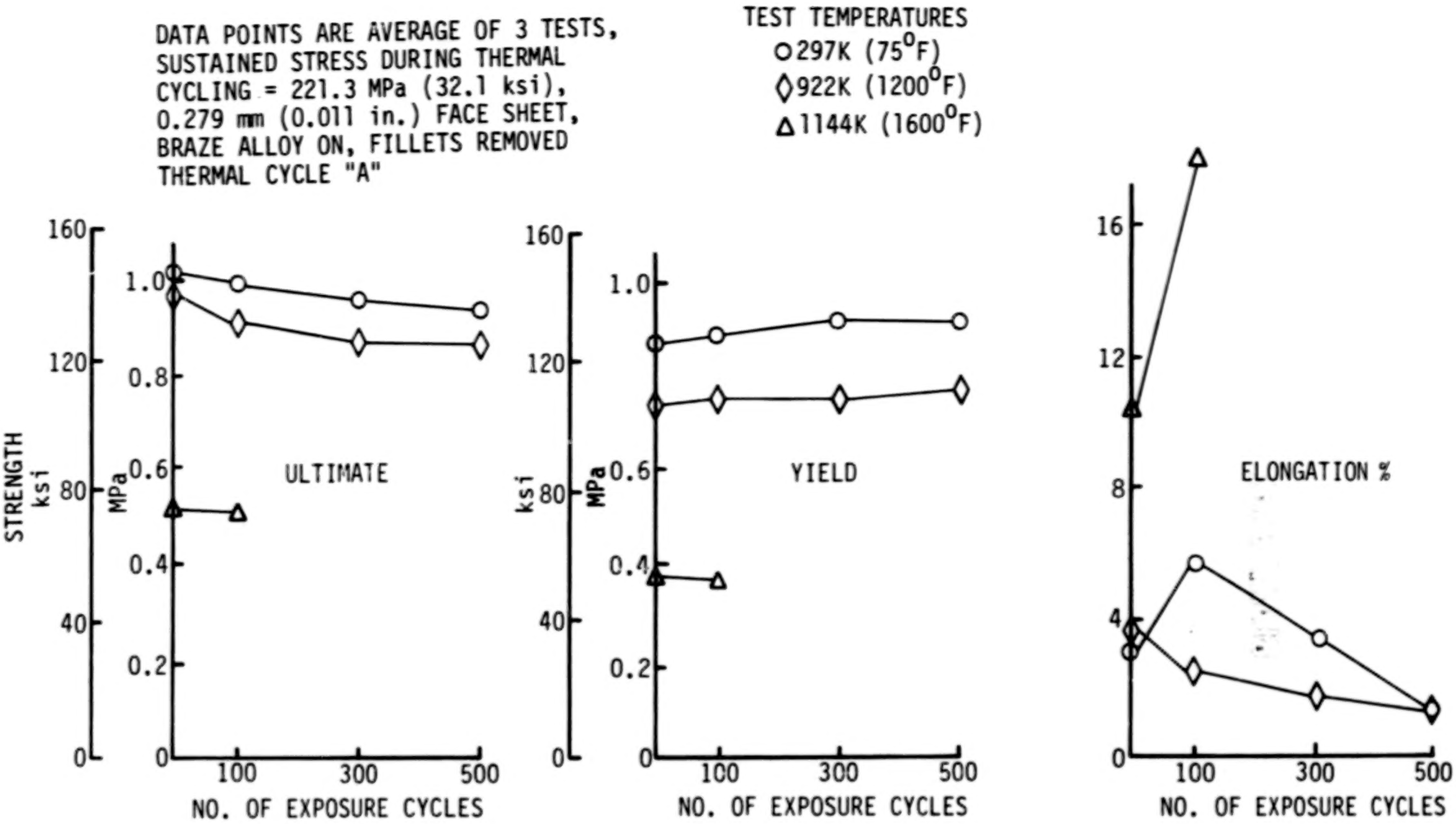


Figure C-3:
Tensile Predictions and Test Data vs
Temperature, 0.533 mm Face Sheet



1 HEAT TREATED PER BRAZE CYCLE CONDITIONS

Figure C-4
Room Temp. Tensile Properties vs Specimen Configuration.



DATA POINTS ARE AVERAGE OF 3 TESTS,
SUSTAINED STRESS DURING THERMAL
CYCLING = 221.3 MPa (32.1 ksi),
0.279 mm (0.011 in.) FACE SHEET,
BRAZE ALLOY ON, FILLETS REMOVED
THERMAL CYCLE "A"

Figure C-5:
Effect of Thermal Cycles on Residual Strength.

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APPENDIX D

EXPLORATORY EDGEWISE COMPRESSION CYCLIC THERMAL EXPOSURE TESTING

APPENDIX D

Exploratory Edgewise Compression Cyclic Thermal Exposure Testing

Table D-1 shows a chronological listing of exploratory tests conducted on the original edgewise compression specimen in an attempt to define the interaction of externally applied loads and thermal cyclic life. The specimens were found to fail at very short life due to creep dimpling of the face skin. Thermal survey tests indicated large transient thermal gradients in the end areas of the specimen. These gradients were caused by the combined effects of the end potting compound and the cool loading head. An analysis was conducted using the BOPACE computer program to define the thermal stresses imposed on the specimen. Results shown in Figure E-1 indicate thermal stresses as high as 128 MPa (18 ksi) were imposed. Results of these exploratory tests were used to establish the combination of 69 MPa (10 ksi) applied stress with a "slow" thermal cycle and peak temperature of 1033K (1400°F) (Cycle C) used for the thermal exposure specimens plotted in Figures 34 and 35 in the body of this report.

Thermal exposure cycling of the 0.279 mm (0.010 in.) face edgewise compression specimens was initiated with a 172 MPa (25 ksi) constant stress (0.6 F_{cv}) applied to the #1 test specimen. The specimen failed after 27 thermal cycles due to intracell creep dimpling of the face skins. A combination of high thermal gradients and creep buckling produced these dimples which progressively got larger until failure.

Several tests (#2 through #7) were conducted in an effort to identify the causes of this problem. The results indicated the rapid thermal cycle (Cycle "A" per Fig. 3) along with the high load level and 1144K (1600°F) temperature were the source of the problem.

In order to meet the original intent of the thermal exposure tests (i.e., to establish residual strength after thermal exposure under load), the thermal cycle and constant stress were revised. A revised thermal cycle of 13.5 minutes per cycle was established and the stress level was decreased from 172 to 69 MPa (25 ksi to 10 ksi).

The next specimen (#8) failed prematurely after 84 cycles due to a shear crimp adjacent to the potted end. Investigation revealed the potting compound had attacked the Rene'41 honeycomb core material (see Fig. 37). Study of other elevated temperature edgewise compression and barrel compression specimens showed this attack was occurring in all specimens tested above 922K (1200°F).

End fixture clamps were installed to stabilize the specimens in the deteriorated areas adjacent to the potting compound. The clamped specimen (#9) survived 79 cycles and again failed by intracell creep dimpling. The end clamps kept the ends cool resulting in greater temperature gradient stresses which led to severe dimpling on this specimen.

The maximum thermal cycle temperature was dropped form 1144K (1600°F) to 1033K (1400°F) to reduce the attack and the end clamps were removed to reduce the temperature gradient stresses. Specimen #10 was successfully exposed to 100 cycles using this test setup and thermal cycle.

Table D-1: Summary of Preliminary Cyclic Exposure Testing

TEST	SPECIMEN	CONSTANT APPLIED STRESS	TEST CONDITION	COMMENT
1	E7L-6H	172 MPa	RAPID CYCLE, 1144K	FAIL AT 27 CYCLES. CREEP DIMPLING.
2	E7L-7H	124 MPa	RAPID CYCLE	DIMPLED AT ≈ 90 CYCLES, 0.51 mm MAX PEAK TO PEAK AFTER 100 CYCLES.
3	E8L-4	172 MPa	SLOW HEAT UP; HOLD 2 HRS 1144K	DIMPLED, 1.02 mm MAX PEAK TO PEAK AFTER 2 HRS.
4	E8L-6H	69 MPa	SLOW HEAT UP; HOLD 2 HRS 1144K	NO DIMPLE.
5	E8L-11	0	SLOW HEAT UP TO 1144K; 5 MIN SOAK	FAIL BY INTRACELL BUCKLING AT 334 MPa.
6	E9L-11	0	STATIC TEST TO FAIL IN 2 MIN	PROPORTIONAL LIMIT ≈ 241 MPa.
7	E7L-5H E9L-8H E-9L-7H	69 MPa	SLOW CYCLE; 1144K MAX 7 CYCLES	NO DIMPLE.
8	E8L-5H	69 MPa	SLOW CYCLE; 1144K MAX	FAIL AT 84 CYCLES; SHEAR CRIMP DUE TO CORE DETERIORATION.
9	E7L-8H	69 MPa	SLOW CYCLE 1144K MAX; ENDS CLAMPED	FAIL AT 79 CYCLES; DIMPLED & CREPT 0.51 mm MAX DIMPLE @ 24 CYCLES. 1.3 mm @ 79 CYCLES.
10	E8L-8H	69 MPa	NO CLAMP, PROPOSED SLOW CYCLE 1033K MAX	NO DIMPLE AT 100 CYCLES; STATIC TESTED 344 MPa; FAIL BY INTRACELL BUCKLING.

NOTE: ALL SPECIMENS 0.279 mm FACE THICKNESS, 6-15 CORE, 0.093 gm/cm^2 BRAZE ALLOY.

APPENDIX E

DEVELOPMENT OF ANALYSIS PROCEDURE

DEVELOPMENT OF ANALYSIS PROCEDURE

Thermal Stresses

Analysis methodology was developed to compute thermal stresses in the panel face sheets caused by transient temperature gradients which may occur during testing. This method used the BOPACE nonlinear finite element computer program incorporating three-dimensional brick elements. Nonlinear thermal expansion is incorporated in the BOPACE program as well as time dependent creep characteristics of the materials. Results of an example analysis are shown in Figure E-1 for the original edgewise compression specimen with a thermal gradient of 700K (800°F) near the ends of the specimen.

Creep Dimpling of Honeycomb Face Sheet

A BOPACE computer analysis was conducted to describe the progressive creep dimpling of honeycomb face sheet under conditions of cyclically varying temperature and load. This solution was used to predict the behavior of the modified edgewise compression specimens at various stress levels and temperatures with results shown in Figure E-2. The computer model (Fig. E-3) utilized for this solution used the nonlinear creep and linear thermal expansion characteristics for Rene'41 shown in Figure E-4. The tests summarized in Figure 33 were originally intended to verify this analysis. However, the specimens failed by shear crimping (prior to any discernible intracell dimpling at stresses and/or cyclic lives considerably lower than those predicted by Figure E-2. We conclude this analysis is not applicable for the 0.533 mm (0.021 in.) face sheet and 6-15 core material, however, it may be valid for heavier core with increased shear crimping and face wrinkling resistance or for thinner skin gages.

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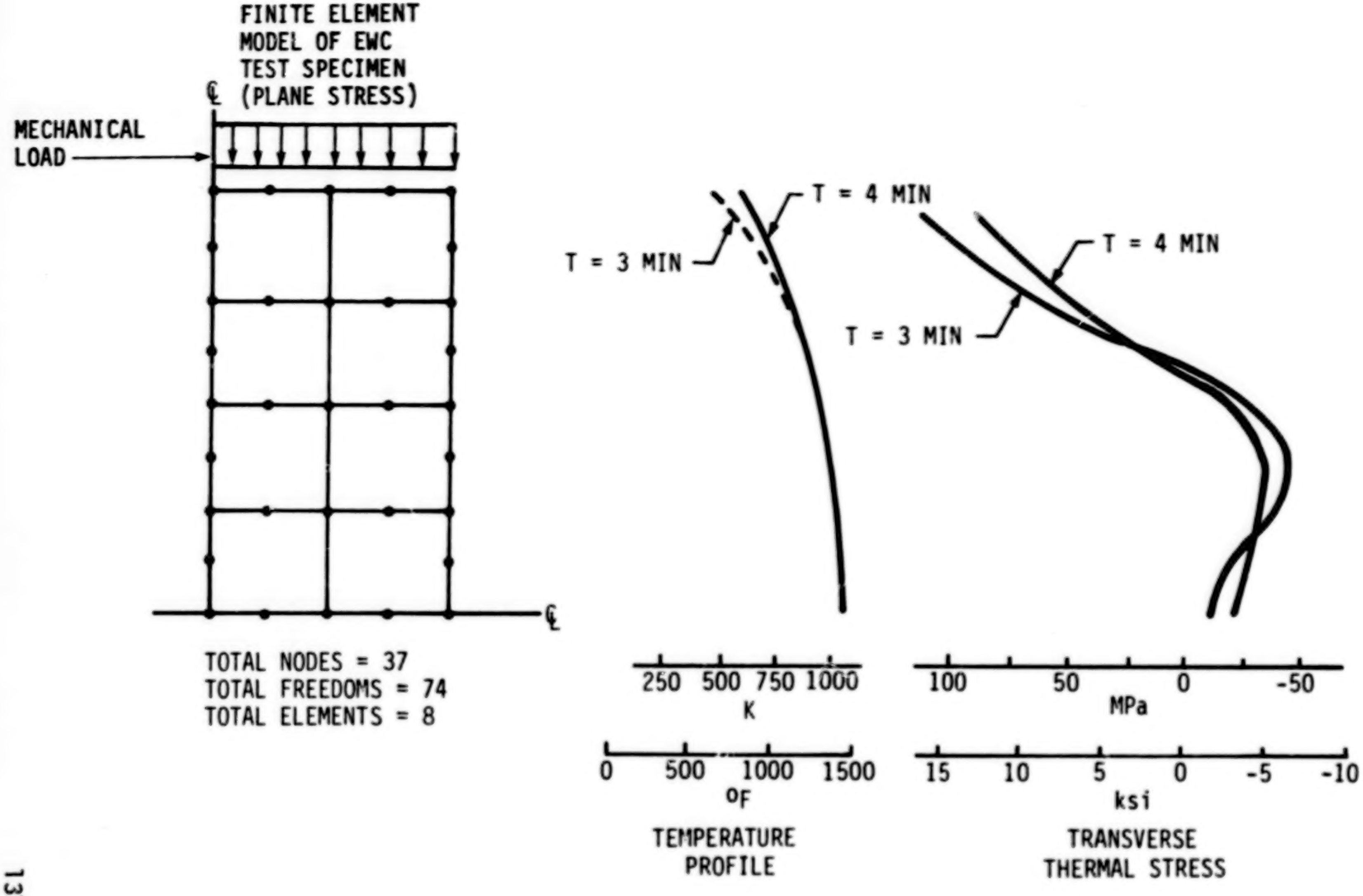


Figure E-1:
Bopace Model for Thermomechanical Loading of Face Sheets and Analysis Results.

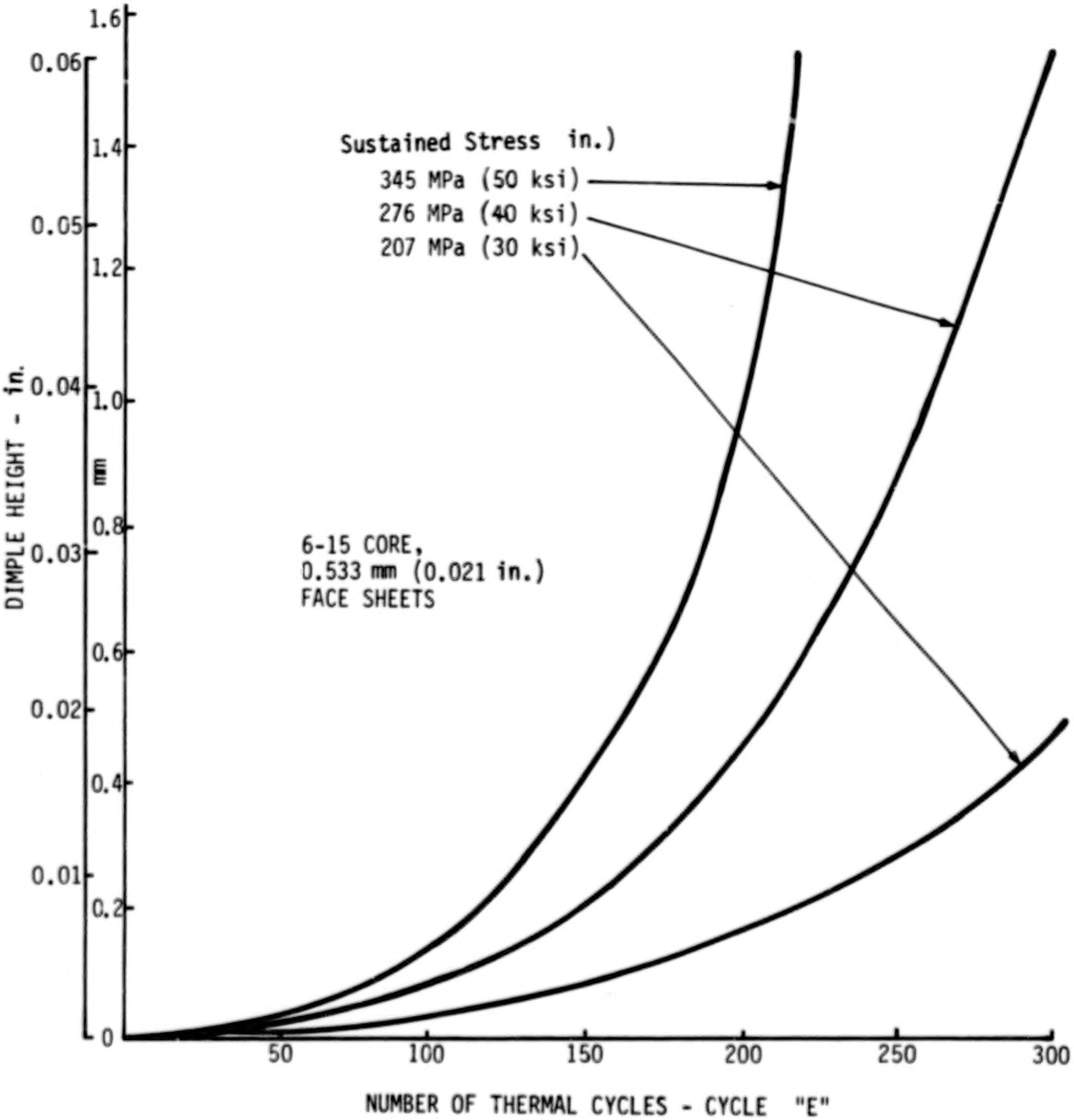
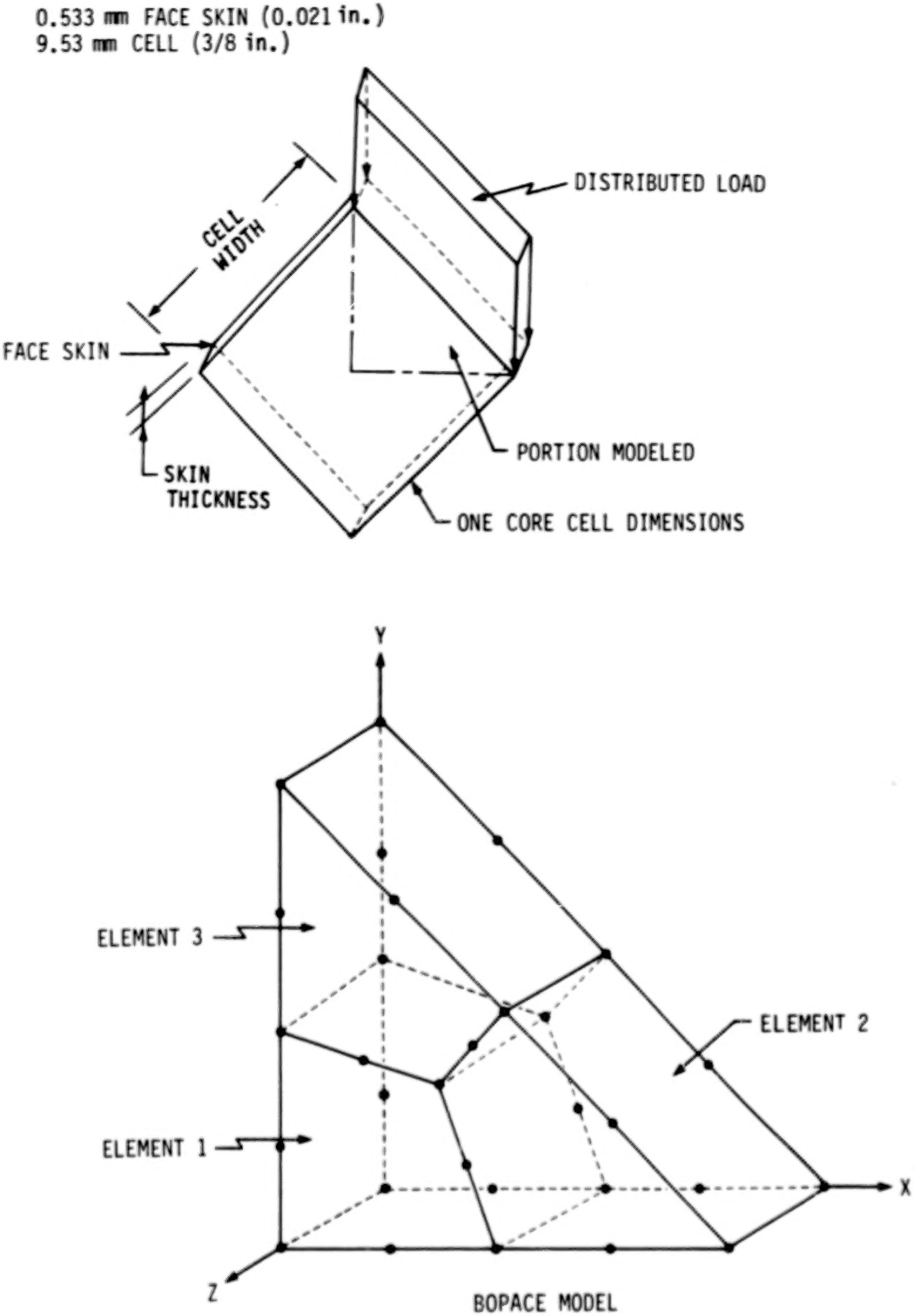


Figure E-2
Bopace Program Prediction of René 41
Honeycomb Sandwich Creep Dimpling.


0.533 mm FACE SKIN (0.021 in.)
9.53 mm CELL (3/8 in.)
DISTRIBUTED LOAD
CELL WIDTH
FACE SKIN
PORTION MODELED
SKIN THICKNESS
ONE CORE CELL DIMENSIONS
Y
ELEMENT 3
ELEMENT 2
ELEMENT 1
X
Z

BOPACE MODEL

Figure E-3
Bopace Model of Single Cell for Creep Dimpling Solution.

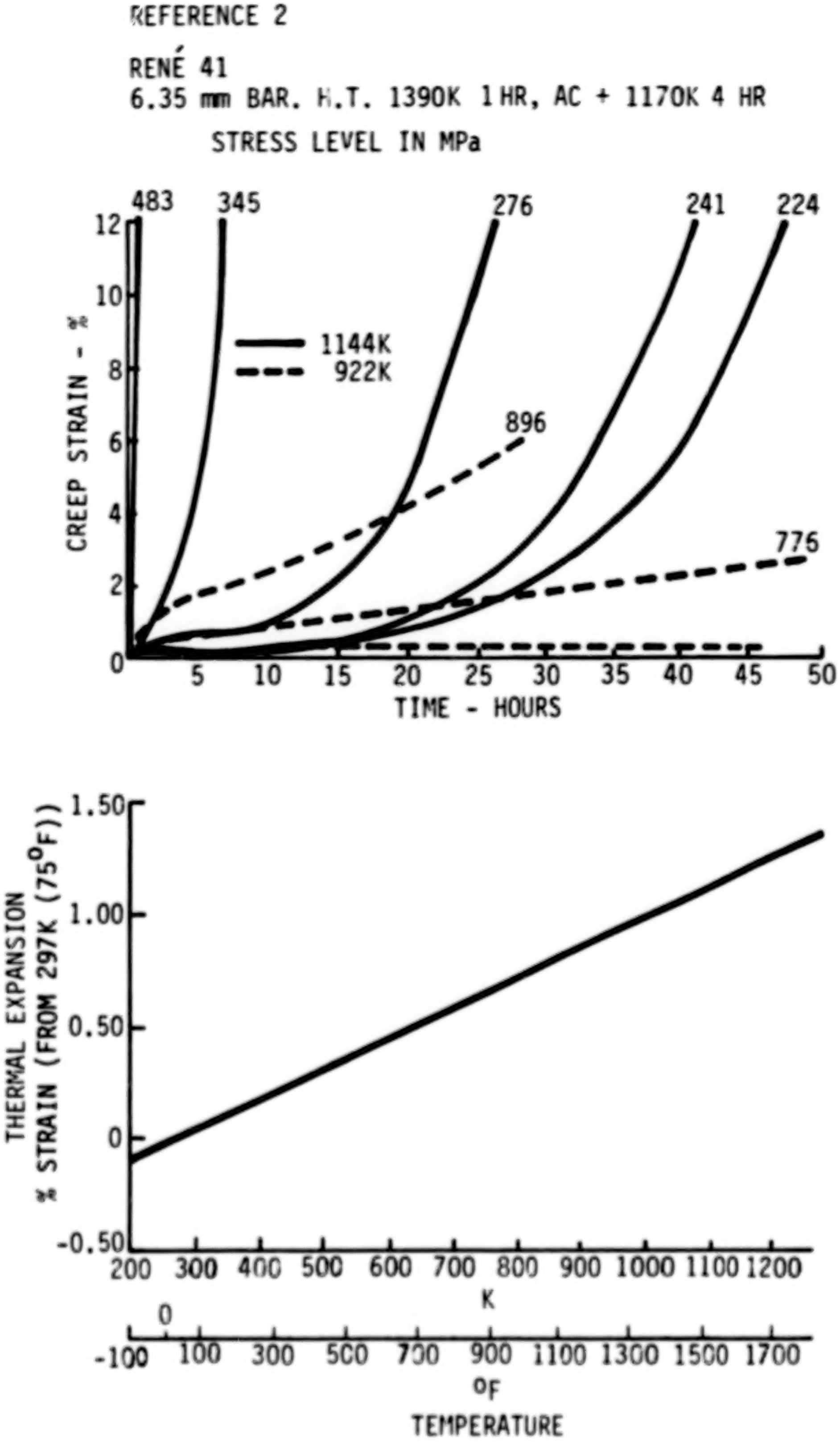


Figure E-4: Analysis Input Data.

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16. Abstract

The objective of this program was to develop preliminary mechanical design properties for brazed Rene'41 honeycomb sandwich. Strength data, creep data and residual strength data after cyclic thermal exposure were obtained at temperatures from 78K to 1144K (-320°F to 1600°F). The influences of face thickness, core depth, core gage, cell size, and thermal/stress exposure conditions on the mechanical design properties were investigated.

A braze alloy and process was developed that is adequate to fully develop the strength of the honeycomb core while simultaneously solution treating and aging the Rene'41 face sheets.

New test procedures and test specimen configurations were developed to avoid excessive thermal stresses during cyclic thermal exposure.

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